COMFORTABLE AND USABLE LOCOMOTION TECHNIQUES IN VIRTUAL REALITY

by

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A DISSERTATION SUBMITTED IN A PARTIAL FULFILMENT FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY IN
HUMAN INTERFACE TECHNOLOGY IN
THE HIT LAB NZ, UNIVERSITY OF CANTERBURY

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Abstract

Locomotion in Virtual reality (VR) is still an open problem with half solutions. A broadly applicable locomotion technique that is easy to use and addresses the issues of comfort and usability has yet to be developed. In this dissertation, we introduce *Multi-Travel mode* that gives users choice to switch between different locomotion techniques based on the Virtual Environment, task and personal preference. This dissertation addresses the thesis: *Users prefer Multi-Travel mode to a single travel mode based on user's tasks and goals in complex VEs.*

An ideal locomotion technique optimizes the user's performance, comfort and user experience. Keeping the characteristics of an ideal locomotion technique as context, we developed TriggerWalking; a Bio-mechanically inspired locomotion user interface for efficient, realistic virtual walking. In the evaluation, TriggerWalking had better usability and comfort compared to other commonly used Teleportation and Joystick locomotion techniques. However, TriggerWalking is suitable for small-scale or medium-scale environments. We speculate that it is not suitable for large-scale environments since it might induce finger fatigue after prolonged use due to trigger-press for each step. Since TriggerWalking uses both the controllers, it is not suitable for tasks that involve the need for interaction using controllers. A single locomotion is not suitable to be used in environments of different sizes and various travel tasks.

Hence, we introduced the concept of *Multi-Travel mode(M-Travel mode)* that has a suite of locomotion techniques to travel in a complex VE and accomplish several travel tasks. The locomotion techniques included in the M-Travel mode are chosen based on the size of the environment and the travel tasks. To enable systematic evaluation of locomotion techniques suitable for a particular VE and travel tasks, we developed a Locomotion Usability Test Environment (LUTE) that accommodates short-, medium- and long-distance travel tasks. We implemented two versions of M-Travel mode: 1. M-Travel mode with pre-selected locomotion techniques, 2. M-Travel mode with locomotion choice.

Our hypothesis was ”TriggerWalking and Multi-Travel mode are two novel locomotion interfaces that are both comfortable and usable”. The implementation of M-Travel mode with pre-selected locomotion techniques had Teleportation, TriggerWalking, and Thumb-Pad locomotion. Based on the travel task, we chose the locomotion

technique that the user can use. We conducted a user study to compare M-Travel mode (pre-selected) to using a single locomotion technique (Teleportation and Thumb-Pad locomotion) in a complex VE and found no evidence that users prefer M-Travel mode (pre-selected) than a single locomotion technique.

Next, we implemented M-Travel mode that allowed users to switch/prefer different locomotion techniques (Teleportation, TriggerWalking, and Walking-in-Place) based on the task. To evaluate M-Travel mode (user-selected) and understand the behaviour of participants in switching locomotion techniques, we conducted a user study that had training and testing sessions. Participants were trained in each of the locomotion technique included in the M-Travel mode (user-selected) in the first session. In the second session, participants completed different travel task in complex VEs. All of the participants switched between locomotion techniques and reported that it was easy and natural to switch. From the interviews with participants, we found that all the participants preferred and used M-Travel mode to complete the tasks in complex VEs. M-Travel mode (user-selected) with a suite of travel techniques carefully selected based on the VE and the travel tasks can be a better solution for locomotion in complex VEs.

Acknowledgments

I would like to thank my supervisory team, starting with Prof. Rob Lindeman for his incredible support and guidance throughout my PhD. He encouraged me constantly and created an active and positive atmosphere around the lab. He is one of my best teachers and taught that if the work is good, everything else falls in place and I will follow that for the rest of my career. My special thanks to Simon Hoermann and Sungchul Jung for all the thought-provoking sessions and for your time.

I feel deeply humbled by the mentoring I received from Mary Whitton. Her questions were tough, and I can definitely say that they have made my vision clear to me. I am grateful for all her help in redesigning my dissertation and making writing meaningful and fun. I also thank her for showing understanding during my failures and for supporting me throughout my PhD.

I owe a multitude of thanks to Prof. Frank Steinicke for his guidance and help in my initial stages of PhD. I consider his sabbatical in HIT Lab NZ as the most productive phase in my PhD.

My special thanks to my best friend, Ramya, for being my strength in all hardships. I am grateful for all the support of my friends Praveen, Prasanth, Adarsa, Varsha, Lavanya, Alaeddin, Humayun and Nikita.

I cannot even begin to thank my parents and my brother for their love and support to make this possible. Coming from a very humble background, they have allowed me to explore my abilities and reach out to the world even though it was scary for them.

I am blessed to have had the opportunity to spend three and a half years at the HIT Lab NZ. It has been my pleasure to work alongside brilliant scientists and engineers of HIT Lab NZ who graciously shared their expertise and time. I thank you all.

To my dad, for his affection,
To my mom, for her strength,
To my brother, for his inspiration, and
To my partner, for his fast cars

Glossary

Comfort is absence of unease and pain.

Complex VE is a combination of different spaces of size and composition (obstacles).

Cybersickness is ”is a condition that may occur during or after exposure to a virtual environment and it can induce symptoms like headache.

Large-scale environment is a environmental space requiring long-distance travel.

Locomotion is ”a change in the viewpoint of the user”.

Medium-scale environment is a non-manipulable object space requiring medium-distance travel.

Navigation is ”user ability to move in an environment”.

Presence is ”Sense of being there”.

Small-scale environment is a manipulable object space requiring short-distance travel.

Usability is the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.

User Experience is a person’s perceptions and responses resulting from the use and or anticipated use of a product, system or service.

Virtual Environment (VE) is an interactive, virtual image display enhanced by special processing and by non-visual display modalities, such as auditory and haptic, to convince users that they are immersed in a synthetic space.

Virtual Reality (VR) is a medium composed of interactive computer simulations that sense the participant’s position and actions, providing synthetic feedback to one or more senses, giving the feeling of being immersed or being present in the simulation.

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Chapter 1

Introduction

In the real world, people use different modes of transportation and locomotion when they are travelling different distances and performing different tasks: We use motor vehicles for long and medium distances, e.g., trips across the country for recreation or across town for shopping, and we walk for medium and short distances, e.g., when picking flowers or working in a building. People choose a method of travel that meets their preferences, travel distance, and task requirements. The question we address in this dissertation is whether it will improve VR experiences to have an Multi-Travel mode (M-Travel mode) that has a suite of locomotion techniques available in the application. This dissertation validates the following thesis: *"TriggerWalking and Multi-Travel mode are two novel locomotion interfaces that are both comfortable and usable"*. We also study if switching between locomotion techniques for various travel distances impacts mental fatigue.

The remainder of this chapter includes relevant definitions, discusses the need for M-travel mode, and outlines the remainder of the dissertation. The remainder of the dissertation is organized as follows: Chapter 2 discusses human factors considered in this dissertation, locomotion techniques developed previously and characteristics of an ideal LUI. Chapter 3 discusses a novel locomotion technique TriggerWalking and its usability studies. Chapter 4 introduces a locomotion evaluation framework and a test bed LUTE for systematic usability studies. Chapter 5 introduces the M-Travel mode with experimenter selected locomotion techniques and its evaluation. Chapter 6 discusses the M-Travel mode with three locomotion techniques for the user to choose from based on task, VE, and preference. Further, we discuss the user study we conducted to analyse the preference of user choosing M-Travel mode to using just a single travel mode. The final chapter 7, revisits the thesis statement, concludes this work, and presents future work. The appendix provides further details on questionnaires used in the usability studies.

1.1 Definitions

According to Sherman and Craig, ”*Virtual Reality (VR)* is a medium composed of interactive computer simulations that sense the participant’s position and actions, providing synthetic feedback to one or more senses, giving the feeling of being immersed or being present in the simulation” [138]. *Virtual Environment (VE)* is an interactive, virtual image display enhanced by special processing, and by non-visual display modalities, such as auditory and haptic, to convince users that they are immersed in a synthetic space.

Freundschuh and Egenhofer [48] define a space that is smaller than the human body as ”manipulable object space,” and space that is greater than the human body, but less than the size of a building, as ”non-manipulable object space.” Space which is between the size of building space and city-size space, is termed ”environmental space.” We relate those terms to travel distances in this way: manipulable object space is a Small-scale environment requiring short-distance travel, non-manipulable object space is a Medium-scale environment requiring medium-distance travel, and environmental space is a Large-scale environment requiring long-distance travel. A *Complex VE* is a combination of spaces that have different sizes and composition (obstacles).

The ability to fool senses enough to make user feel present in a virtual environment has many potential applications. However, the biggest barrier to wide adoption of VR is lack of a good usability and user experience design. The official ISO 9241-11 definition of *Usability* is the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use. *User Experience* is a person’s perceptions and responses resulting from the use and/or anticipated use of a product, system or service.

Good user experience includes user being comfortable, present and immersed in the VE and improves user’s performance. In this thesis, we have defined *User Performance* as combination of user task performance and subjective response metrics. Task performance is measured by speed and accuracy with which user completes the task. Subjective response metrics are the user’s user comfort and presence while carrying out the tasks in Virtual Environment. User comfort is both Physical and Psychological. *Comfort* is absence of unease and pain. User comfort relates to the ability of user to maintain a comfortable pose or perform the tasks in VR for longer times. Presence is ”Sense of being there” [22].

1.2 Locomotion in VR

Pimentel and Teixeria [120] state that absolute realism is not necessary to create a sense of immersion and the VR must be real enough to cause the users to suspend the disbelief for certain time similar to a good movie or a novel. User interaction is a significant component in creating a sense of immersion in the VE. According to Pimentel and Teixeria [120], interactivity has two primary components: navigation and the interaction with the elements in VE. Navigation, in general, is user ability to move in an environment. Navigation consists of two components: Locomotion and wayfinding. Locomotion is a change in the viewpoint of the user. Wayfinding is the user ability to plan the path to the target destination [22]. The terms 'travel' and 'locomotion' are synonyms and we use the terms interchangeably.

A good locomotion technique is expected to optimize factors such as comfort (e.g., lack of cybersickness), precision, accuracy, presence, and learnability [22]. Comfort and usability are two main factors that are considered in the design and evaluation of locomotion techniques in this dissertation. In addition, there are tracking and hardware (sensors, HMD's, etc.) requirements to consider while developing a novel locomotion technique or choosing a locomotion technique for any virtual reality application. By far, the most basic and natural form of active human locomotion is bipedal walking. Hence, natural locomotion user interfaces (LUIs) based on real walking in VEs support a veridical model of reality and have been proven to be benficial for many applications, such as training, rehabilitation, or entertainment. Real walking can be implemented in VEs by, for example, mapping movements of a tracked head-mounted display (HMD) to the virtual camera, thus generating self-motion feedback from the VE by means of, for example, an isometric (one-to-one) mapping [153]. However, a one-to-one mapping between real and virtual motions is often not possible due to the physical constraints of the tracking space or is impossible, for instance, in seated VR experiences.

Virtual travel methods which use magical interaction metaphors (magical metaphors) such as Teleportation and portals are particularly useful for moving in larger spaces but have been shown to reduce the sense of presence, spatial awareness and spatial cognition [158]. Passive travel, such as joystick, where the user is moved along by the system, is notorious for inducing cybersickness and nausea according to sensory-coflict theory [89]. Cybersickness is a set of unpleasant symptoms that are induced by exposure to a virtual environment and can last from a few minutes to even days [125]. Other techniques such as walking-in-place (WIP) or running in place and/or arm swinging use physical gestures, such as walking, running or moving hands to control camera motions. These active approaches provide semi-natural walking experiences that provide vestibular feedback that reduces nausea. However, repetitive physical motions based on leg or arm movements induce fatigue after prolonged use.

Additionally, in most VR applications, locomotion is not the primary task, but it enables the user to accomplish the primary task (e.g., collect objects). A single locomotion technique cannot deliver all the desirable attributes further discussed in Chapter 2. Since a perfect locomotion system has not been designed yet, a better approach is to select the locomotion technique based on the requirements of the application. For example, a locomotion technique using vehicular or magical metaphor is suitable if the user must travel a large distance, while walking-in-place (WIP) is more useful for walking around room-scale virtual environments. Another task may need to use the hand controllers for interacting with objects, making them unavailable for locomotion control. Different applications need locomotion methods based on different factors, such as tracking space size, which locomotion parameters can be controlled, user posture (seated or standing), physical activity, etc.

Hence, several factors influence the suitability of a locomotion technique to a particular task. To narrow the scope of our research, we limited our work to:

- Locomotion techniques that are developed for consumer-grade HMDs such as HTC Vive, Oculus Rift, and Sony PSVR.
- Locomotion techniques that do not include any motion platforms.
- Locomotion techniques that do not use any additional high-end hardware such as treadmills.
- Locomotion techniques that use at most room-scale tracking similar to the tracking provided by HTC Vive.
- Human factors such as comfort and usability [22] .
- Locomotion techniques that support both seated and standing user postures.

1.3 Thesis Statement

Boletsis [11] conducted a systematic literature review of locomotion techniques and the studies conducted to evaluate their performance and usability. The results of the review showed a system-centric instead of user-centric approach towards research issues in the study of VR locomotion. User performance in a locomotion technique can only be maximized by considering the needs of the user.

In this dissertation, our first assertion is *"an ideal locomotion technique has high user comfort and high usability"*. Chapter 2 discusses the concepts and factors affecting the comfort of the user. The chapter also reviews previously developed locomotion techniques and their limitations. The final section of chapter 2 discusses the characteristics of an ideal locomotion technique.

Keeping characteristics of ideal locomotion technique in context, chapter 3 discusses our design approach in developing and evaluating TriggerWalking. In this dissertation, our second assertion is *"TriggerWalking is a comfortable and usable locomotion technique"*. In addition, the following are discussed:

- a kinematic analysis of head oscillations of users' walking while wearing an HMD,
- an initial evaluation of the effects of simulated walking oscillations (induced by trigger pulls) on walking performance and spatial cognition, and
- a confirmatory study to compare TriggerWalking with WIP, Teleportation, and Joystick locomotion techniques.

Results from two user studies suggested that although TriggerWalking has high usability and comfort, prolonged use could lead to finger fatigue. To accomplish tasks in a complex VE, a single locomotion technique is not enough: there is a need for a M-Travel mode that has a suite of locomotion techniques. Locomotion techniques included in the M-Travel mode must be selected such that they provide locomotion for different tasks and distances in complex VE, for example, if the complex VE needs the user to follow a long road, enter a room, and search for treasure. M-Travel mode must give the user a choice of locomotion techniques so they can both efficiently travel long distances and move around in the room to collect treasure.

There is a need to systematically evaluate the locomotion techniques using a common testbed to find the locomotion techniques best fit for a task and VE. However, a framework that helps us select suitable locomotion techniques is yet to be developed. Chapter 4 discusses a locomotion evaluation framework to systematically evaluate a locomotion technique for a given task and Environment. Chapter 4 also introduces a novel Locomotion User Evaluation Testbed (LUTE) that includes environments of different size which has the ability to accommodate different tasks and locomotion techniques.

This dissertation addresses the thesis: *Users prefer M-Travel mode to a single travel mode based on the user's tasks and goals in a complex VE.* The validity of this thesis is demonstrated in the results of two user studies (Chapter 5 and 6). The first user study in Chapter 5 evaluated a M-Travel mode having experimenter assigned locomotion techniques for different tasks. We selected the locomotion techniques that must be used by the user in each task scenario based on the performance of locomotion technique in similar tasks in previous literature. There was no significant improvement in usability for M-Travel mode compared to Teleportation and Thumb-pad navigation. However, M-Travel mode had significantly lower sickness scores than Thumb-pad navigation.

The second user study, in Chapter 6, evaluated a M-Travel mode with user choice to switch/change between Teleportation, TriggerWalking, and Walking-in-Place. The participants were trained to proficiency in each technique before completing the tasks in a complex VE. Given that users are trained to proficiency, the results of the study demonstrate that:

1. Users found it easy to switch between different techniques.
2. Users preferred different locomotion techniques based on travel distance and complexity of the VE.
3. Users preferred having a choice to switch between locomotion techniques rather than having a single locomotion technique to complete various tasks in a complex VE.

Chapter 7 revisits the thesis statement and discusses conclusions derived from each chapter, and provides design recommendations for researchers and VR game developers.

1.4 Publications

The following papers have been published as part of this thesis. The user studies included were designed, implemented and evaluated by the author.

[1] **Bhuvaneswari Sarupuri**, Miriam Luque Chipana, and Robert W. Lindeman. 2017. Trigger Walking: A low-fatigue travel technique for immersive virtual reality [Poster]. In Proceedings of the 2017 IEEE Symposium on 3D User Interfaces (3DUI), Los Angeles, CA, , pp. 227-228. doi: 10.1109/3DUI.2017.7893354

[2] **Bhuvaneswari Sarupuri**, Simon Hoermann, Frank Steinicke, and Robert W. Lindeman. 2017. Triggerwalking: a biomechanically-inspired locomotion user interface for efficient realistic virtual walking. In Proceedings of the Symposium on Spatial User Interaction (SUI '17). Association for Computing Machinery, Brighton, United Kingdom, 138–147. DOI:https://doi.org/10.1145/3131277.3132177

[3] **Bhuvaneswari Sarupuri**, Simon Hoermann, Mary C. Whitton, and Robert W. Lindeman. 2017. Evaluating and comparing game-controller based virtual locomotion techniques. In Proceedings of the 27th International Conference on Artificial Reality and Telexistence and 22nd Eurographics Symposium on Virtual Environments (ICAT-EGVE '17). Eurographics Association, Adelaide, Australia, 133–139.

[4] **Bhuvaneswari Sarupuri**, Simon Hoermann, Mary C. Whitton, and Robert W. Lindeman. 2018. LUTE: A Locomotion Usability Test Environment for Virtual Reality. In Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games), Wurzburg, 2018, pp. 1-4. doi: 10.1109/VS-Games.2018.8493432

[5] **Bhuvaneswari Sarupuri**. 2018. Comfortable and Efficient Travel Techniques in VR [Doctoral Consortium]. In The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings (UIST '18 Adjunct). Association for Computing Machinery, New York, NY, USA, 232–235. DOI:https://doi.org/10.1145/3266037.3266126

Chapter 2

Background

In this chapter, we introduce the concept of locomotion in VR, previous implementations, and motivate why this is an essential area of focus for effective interaction in VR.

2.1 Locomotion in VR

Virtual Reality enables users to experience a synthetic world. According to Bowman and Hodges [19], the basic interactions that are building blocks in VR are *Travel, Selection, and Manipulation*. *Travel* is one of the most basic and universal interactions found in virtual environments. The terms *Travel* and *Locomotion* are synonyms and are hence used interchangeably in this dissertation. Locomotion refers to the user interactively moving from one place to another in a virtual environment. Locomotion can also be defined as the change in the location of the viewpoint. *Navigation* is considered as planning the path (*wayfinding*) and traveling (*travel*) through space [19]. In general, the virtual world is larger than the real tracked world. So the challenge is to design a travel technique that maps the infinite virtual space onto the finite tracked space without inhibiting the user's sense of presence. In this section we discuss different types of locomotion techniques: vehicular, natural, semi natural and non-natural locomotion techniques.

Different taxonomies have been introduced to classify the locomotion interfaces. Each taxonomy is unique since the authors had a specific goal in their minds while classifying the interfaces [19, 4, 104, 94]. For example, Bowman et al. [19] classified the travel techniques for Immersive Virtual Environments (IVEs) based on target selection, velocity, acceleration selection and input conditions. Arns divided the locomotion broadly based on rotation and translation, with each component being physical or virtual [4]. More recently Bowman et al. [103] developed a taxonomy exclusively for locomotion techniques based on walking. These walking-based techniques were divided according to movement range (stationary, small range of movement ($< 1m$), and large range of movement ($> 1m$)), walking surface, transfer function (mapping between input and output), and input properties sensed (body parts tracked and properties (position and motion) tracked). In this dissertation, we classify locomotion techniques based on the degree of naturalness into broad categories of vehicular, natural, semi-natural and non-natural locomotion.

2.1.1 Vehicular Locomotion Techniques

A locomotion interface is classified as vehicular if the technique allows users to produce movement by interacting with the interface of a vehicle. *Sensorama* by Heilig [53] allowed users to passively experience a motorcycle ride through New York. An application of VR is flight simulation, used for training and assessing pilots [81, 8, 65]. Other motorized vehicles including cars [27], ships, trucks and buses [57] are also used to experience navigation in IVR. Even though some vehicle simulators are stationary, multi-sensory feedback such as auditory [165] and vibrotactile [173] make the simulation compelling.

6DOF motion platforms create real sense of motion. For example, the Desdemona simulator[1] installed by TNO[2] is used for advanced flight, driving and sailing simulations. It allows 2 meters of vertical movement and 8 meters of horizontal movement. The 6DOF platform can generate up to 3G of force. Toyota has developed a simulator project at their Higashi Fuji Technical Center[3]. Its purpose is to analyze the greatest factors contributing to accidents and develop safety technology that helps prevent accidents. Max Planck Institute CyberMotion simulator[4] has an enclosed cabin with a curved projection screen. It can be used for passive movement of the participants along a predefined trajectory. 6DOF can also be divided into small envelope[5] and large envelope motion platforms[6] based on their size.

2.1.2 Natural locomotion techniques

Physical walking is the natural way of travelling in a 3D world [174]. Natural locomotion techniques use biomechanics of walking to travel in Virtual Environment.

Bio-mechanics of Walking

The act of walking can be expressed as repeated gait cycles which are the period from initial contact of one foot until the same foot makes contact again. Each gait cycle is divided into two phases: the stance phase and the swing phase. The change in walking velocity depends on the duration of stance and swing phases [101].

A general equation for finding walking velocity ($|v|$) is given by Equation 2.1

[1] $http://www.desdemona.eu/desdemona.html$
[2] https://www.tno.nl/en/
[3] $http://www.toyota.com.cn/innovation/safety_technology/safety_measurements/driving_simulator.html$
[4] $http://www.cyberneum.de/facilities-research/cmslab.html$
[5] http://fullmotiondynamics.com/
[6] $http://www.desdemona.eu/desdemona.html$

$$|v| = f \times l \tag{2.1}$$

where f is the step frequency and l is the step length. However, there are many other walking models. Dean [40] has proposed a relationship between walk speed ($|v|$), step frequency (f) and height of the user (h) given by Equation 2.2

$$|v| = \left(\frac{f}{0.157} \times \frac{h}{1.72}\right) \tag{2.2}$$

In Dean's equation, the walking speed is related to height of the user which in turn is related to the stride length, i.e, stride length is related to the height of the user. Bowman et al. [129] describe natural walking as the most direct and obvious technique for travelling in VE. Recent research has focused on making real walking part of navigation since bipedal walking is the basic and natural form of locomotion for humans. The two primary purposes of walking, according to Steinicke et al. [153] are for (1) movement and (2) sensory awareness cues such as visual information, vestibular information and proprioceptive information. Virtual environments can benefit from enhanced immersion and presence if the locomotion in these environments mimics natural human walking.

One of the most popular and efficient travel techniques to map infinite virtual space to limited tracked space is Redirected Walking (RW) [123]. In RW techniques, user's physical transformations are not mapped 1:1, or the physical characteristics of the VE is manipulated. These manipulations allow the user to be guided in a physical path that is mapped to a larger VE. Nilsson et al. [110] summarizes 15 years of research on redirected waling in immersive VE and explains the different approaches and challenges.

Redirected walking works well only when the tracked space is larger than 30mx30m [12] and introduces visual-proprioceptive conflict if the tracked space is smaller [23]. Suma et al. [158] provide a taxonomy for redirection techniques depending on geometric applicability (Repositioning techniques and Reorientation techniques) and likelihood that they will be noticed by the users. Adding translation gain improved the spatial awareness and accurate distance estimation in a virtual environment [86]. Integrating passive haptics into redirected walking techniques improved the experience by including the sense of touch [79]. Redirected interfaces partially address the issues of travelling in large virtual spaces. However, they need reasonably large physical spaces to travel. These techniques do not work well if the application is not well suited for redirection. For example, safety concerns arise if the user has to run or have a sharp turn around in the virtual world, or if the user is near the boundary of tracked space.

Steinicke et al. [152] analyzed human sensitivity to redirection techniques and found that users can have physical rotation about 68% more or 10% less than perceived virtual rotation in VR. The users are found to be more sensitive to scene motion if scenes move against head rotation [152]. Though Redirected walking techniques are natural and improve presence, the user has to physically carry equipment such as cables, which induces fatigue over time. One natural walking technique which uses a magical metaphor to navigate large environments is ”seven-league boots ” [58]. In this technique, each step is scaled by 7 to allow the user to navigate large distances faster. Table 2.1 summarizes the implementations of redirected walking based on continuity in the movement and the gain. Suma et al. [158] designed a taxonomy for deploying redirected techniques in immersive VE. They conducted a user study of three reorientation techniques and found that participants were less likely to break in presence when reoriented using the techniques that are subtle.

Table 2.1: Summary of redirection techniques

RW	Year	**Continuity**		**Gains**			
		Cont.	Disc.	Rotation	Translation	Curve	Bending
Razzaque et al. [123]	2001	*		*		*	
LaViola et al. [83]	2001	*		*			
Razzaque et al. [124]	2004	*		*			
Nitzsche et al. [111]	2004	*				*	
Williams et al. [177]	2006	*			*		
Williams et al. [178]	2007		*	*			
Interrante et al. [58]	2007	*			*		
Engel et al. [43]	2008	*		*			
Bruder et al. [28]	2009	*	*	*		*	
Steinicke et al. [151]	2009	*			*	*	
Azmandian et al. [6]	2016	*		*	*	*	
Langhbehn et al. [86]	2017	*					*
Vasylevska and Kaufmann [166]	2017	*		*	*		
Strauss et al. [156]	2020	*		*	*	*	
Cao et al. [30]	2020		*	*	*		
Lee et al. [91]	2020	*		*	*	*	

2.1.3 Semi-Natural Locomotion Techniques

Semi-natural locomotion techniques use some of the aspects of the biomechanics of walking. They can be further divided into gait negation techniques and partial gait techniques.

Gait Negation Techniques

Gait negation systems move the user forward in the VE as the user moves back in the physical space. Linear treadmills, omni-directional treadmills, low-friction surfaces and step-based devices all simulate physical walking through treadmill-like devices [27]. Ideally, when users walk on a treadmill, they move the same distance in virtual worlds as they move in real world. Passive treadmills demand much physical effort to move, whereas motorized treadmills reduce fatigue. However, motorized treadmills are both noisy and carry the risk of injury to the user. Earlier treadmills also had issues with orientation and speed. Some treadmills had the option of handlebars for user to hold to while moving similar to the one used by Brooks [26]. Linear treadmills only allow users to move forward, so to move in other directions, the user either navigated with a joystick, or the entire treadmill platform was rotated as in ATLAS [112]. Simulating walking uphill and downhill was not possible using linear treadmills. To address this issue, treadmills with tilting capacity such as Sarcos were designed [56]. Sarcos consists of a large tilting treadmill, an active mechanical tether and a CAVE-like visual display. Unlike these linear treadmills, Omni-directional treadmills allow the user to walk in any direction, but they are mechanically complex [144]. Omni-directional treadmills can be categorized into active and passive. Active treadmills detect the user's walking motions and move accordingly to negate them. Passive Omni-directional treadmills have no external actuation and are mostly driven by weight of the user's body or force exerted by the user's feet.

CyberWalk [144] developed an Omni-directional treadmill, CyberCarpet [137], that enables users to walk in any direction. This treadmill utilizes small balls embedded in the platform to enable users to walk in all directions. They also built a large VR 2D Omni-directional platform that allows unconstrained locomotion. It keeps the user close to the centre by adjusting the speed and direction of the platform. Iwata used a torus-shaped treadmill consisting of 12 individual treadmills to give the user the feeling of natural walking while navigating in VE [63, 62] . A similar locomotion interface, String Walker, used eight strings actuated by motor-pulleys to let the user maintain constant position [64]. Each of these interfaces has the issues of complexity, safety and accurate tracking the location of the user's feet. To solve these issues, Iwata et al. developed an Omni-directional surface called CirculaFloor with sets of movable tiles [60]. To keep the user in limited space while allowing them to move in any direction, a human-sized hamster ball (sphere) called VirtuSphere or CyberSphere was developed [98].

All the locomotion interfaces mentioned above require sophisticated hardware. Difficulties include procuring hardware, calibration, ease of use and safety. Omni-directional surfaces with a low frictional surface such as Virtux Omni, KAT and Cyberith Virtualizer are relatively affordable treadmills. However, because of low

Table 2.2: Progression of gait negation Techniques

Locomotion Interface	Direction	Year	Active or Passive	Additional design specifications
Linear Treadmill with handle support[26]	Linear	1988	Passive	Uses shopping cart metaphor
ATLAS [112]	Linear	1998	Active	Motion platform with 3 axis rotation
SARCOS [56]	Linear	2000	Passive	Tether force can simulate gravity and slope
Torus Treadmill [62]	Omni-directional	1999	Active	12 rotating treadmills and magnetic foot tracking
Virtual Perambulator [63]	Omni-directional	1999	Passive	Tracked roller shoes with toe brake
GaitMaster [61]	Omni-directional	1999	Active	Omni-directional uneven surface
CirculaFloor [60]	Omni-directional	2005	Active	Step based and Omni-directional moveable floor tiles
String Walker [64]	Omni-directional	2007	Active	Uses touch sensors to detect motion
CyberCarpet [137]	Omni-directional	2007	Active	Based on Torus Treadmill with a better control on speed and direction
Cybersphere [98] & Virtusphere	Omni-directional	2008	Passive	Human sized VR “Hamster Ball”
CyberWalk [144]	Omni-directional	2011	Active	Rollerballs on treadmill
Virtuix Omni [7]	Omni-directional	2013	Passive	Natural locomotion
Cyberith Virtualizer[8]	Omni-directional	2013	Passive	
KatVR[9]	Omni-directional	2015	Passive	Free range of motion

friction, the walking experience is more like walking or sliding on a slippery ice surface. GaitMaster is a locomotion interface that can simulate an infinite uneven surface [61]. The 3DOF motion-based mounted turntable is used to trace positions of the foot and orientation of the walker.

There has been much progress in gait negation techniques, and Table 2.2 points out some of the differences to give an idea on the progression of the technology. However, in this dissertation, we restrict our work to locomotion techniques that do not use any specialized hardware for consumer-grade HMD.

Partial Gait Techniques

Partial gait techniques use the gestures of natural gait to locomote. Walking in place (WIP) techniques require the user to produce walking gestures by performing stepping movements [29]. According to Whitton and Razzaque, the three essential characteristics of WIP are as follows [172]:

- Users are standing
- Users move their feet in an up-down fashion similar to the natural walking
- Users are stationary in the lab space

The steps are detected, and the viewpoint in the virtual world is moved accordingly. This technique does not require the user actually to move forward, hence there is no need for space or space tracking. Different sensors are used to detect the user gait events. Table 2.3 summarizes the implementation of speed, direction and the sensors used in the WIP implementations. Bougilla et al. [16] used a 45 square centimetre Plexiglas surface with 60 iron switch sensors to detect the user’s steps [16]. In a study by Bougila et al., users reported ease of use, but some users felt the walking pad was too small [16]. When WIP was compared with mouse-based navigation techniques, users reported that WIP offers more immersion and intuition even though the mouse-based navigation technique was faster [55]. Sensor-Integrated balance board for the Nintendo Wii tracked steps by detecting the change in weight at each corner. Williams et al. found that WIP was perceived as immersive and efficient as using the joystick for navigation [175].

Motion tracking is another popular sensing method for WIP techniques. Slater et al. [143] used neural networks to detect steps based on the head tracking. Usoh et al. [163] compared WIP, push-button flight along the ground plane, and real walking for navigation, finding that WIP induced more presence than flying. However, presence remained better in real walking than in WIP. *Gaiter* is a WIP technique that facilitates forward, backward, lateral and diagonal movements [159]. The study by Whitton et al. [174] compared five techniques: three conditions with HMD (joystick; WIP; real walking) and two conditions without HMD (walking with natural vision; walking with a restricted field of view). Participant's performance (task completion time and score) using WIP and joystick conditions was poor compared to the other conditions and considered as far from real walking. To improve the performance of WIP, Feasel et al. [44] proposed a low-latency version (LLCM-WIP). This technique tracks the user's vertical heel movement to control the viewpoint displacement. It included a low start/stop latencies and smooth step velocities. Human gait analysis is used to improve the WIP technique in Gait-Understanding-Driven WIP (GUD-WIP) [171]. The study conducted suggests that the walking speeds generated from understanding the gait of the users improve the walking experience. Bruno et al. [29] used footstep vertical displacement amplitudes to control the speeds in the VE in their Speed-Amplitude-Supported WIP (SAS-WIP). Studies comparing SAS-WIP and GUD-WIP indicated that SAS-WIP was more efficient and faster than GUD-WIP for long distances and more effective and precise for short distances. Wilson et al. [181] used Kinect sensors to track the user's steps. Tapping in place is another gestural based technique for WIP wherein the user alternately tapped each heel against the ground to locomote [109].

Shadow walking is a WIP technique that enables lateral movements in VE [185]. Using a combination of different sensors, this technique uses different gestures for controlling movements. The system uses a CAVE for the VE, but without a back wall, so when the user makes a full turn, they may face the empty wall, breaking the immersive experience. To avoid this problem, Razzaque et al. [124] proposed a combined RW–WIP technique that ensures that the user is reoriented such that they never face an empty space. However, the study did not report a large difference in the number of times participants noticed the missing back. Hanson et al. [50] developed a WIP technique that uses deep networks. The CNN-WIP is evaluated and compared to the bio-mechanical WIP and a WIP with threshold. The results showed that the CNN technique perfomred better than the other two WIP implementations. Arm-Swinger[10] is a partial gait locomotion technique that uses arm movement of the users to control the locomotion.

[10] $https://github.com/ElectricNightOwl/ArmSwinger$

Table 2.3: A summary of speed, direction control and sensor type of WIP implementations

WIP	Speed Control	Direction Control	Sensing
Slater et al. [143]	frequency (head)	yaw (head)	magnetic
Slater et al. [141]	frequency (head)	yaw (head)	magnetic
Templeman et al. [159]	frequency (knees)	yaw (knees)	inertial and force
Bouguila and Sato [18]	frequency (feet)	yaw (head or torso)	infrared
Bouguila et al. [17]	frequency (feet)	yaw (feet)	pressure
Bouguila et al. [15]	frequency (feet)	yaw (feet)	pressure
Feasel et al. [44]	vertical heel speed	yaw (torso)	optical tracker
Wendt et al. [171]	frequency (knee)	yaw (torso)	optical tracker
Zielinski et al [185]	frequency (feet)	yaw (feet)	optical tracker
Kim et al. [75]	constant (stride length)	yaw (torso)	inertial and ultrasonic
Bruno et al. [29]	feet height	yaw (feet)	optical tracker
Williams [176]	constant	yaw (head or torso)	depth
Nilsson et al. [107]	frequency (feet)	yaw (feet)	optical tracker
McCullough et al. [97]	frequency (arm)	yaw (head)	inertial
Tregillus and Folmer [161]	frequency (head)	yaw (head)	inertial
Bruno et al. [102]	User height, step height, and step speed	yaw (hip)	depth

2.1.4 Non-natural Locomotion Techniques

Virtual Reality gives designers opportunities to create worlds out of their imagination, so locomotion does not necessarily have to follow the rules of the real world. As the name suggests, the locomotion techniques which are independent of any natural locomotion cues are *non-natural locomotion techniques*. They include artificial locomotion using a joystick and locomotion techniques based on metaphors or gestures. Many of the VR games use joysticks to navigate the virtual world since it removes the need for tracking or the additional devices used in natural or semi-natural locomotion techniques. However, simple joystick-based locomotion leads to disorientation and cybersickness due to sensory conflicts [89]. Non-natural locomotion techniques that uses magical metaphors for interaction such as Teleportation and magical portals can be an exciting, easy way of navigating VE.

Teleportation, a magical metaphor technique is probably the most popular navigation method [24]. A user can point to the area they want to go to and teleport there. However, the disadvantage of the technique is its adverse effects on presence. Kelly et al. [69] introduced two versions of Teleportation: partially concordant teleporting and discordant teleporting. Partially concordant teleporting included all the rotational self-motion cues and discordant teleporting included rotational self-motion cues. Results showed that the discordant teleportation led to larger errors in estimation compared to the partially concordant teleporting.

Next, magic wand techniques depict the use of a wand and some spells to navigate through VE [34]. The Jumper Metaphor uses a jumping gesture to travel large distances at an instance [13]. The World-in-Miniature gives the user a miniature version of the space they are in, as well as the location of the user in the space. Such worldlets are 3D thumbnails consisting of a miniature virtual world fragment [42]. Users can save the landmarks or areas of interest in the virtual world and navigate: The user can change the position of the miniature version to move in the virtual world [154]. One study on worldlets found significantly reduced travel time because it eliminate unnecessary backtracking [42] . A leaning-based locomotion interface developed by Wang and Lindeman made use of the Silver Surfer metaphor [169]. VR participants use a flying surfboard to navigate through VE. Finger walking-in-place (FWIP) uses a multi-touch device to enable users to travel in VE with just their fingers [74]. Using FWIP, users have the ability to move forward and backward in the virtual world, as well as rotate and control the speed of movement. However, the sense of presence is reduced compared to Walking in Place (WIP) since it does not provide any vestibular cues. Since the physical motion of FWIP is much less, fatigue is reduced in FWIP. Yan et al. [182] developed a VR travel framework which supports three different travel techniques for different distance ranges which uses a fingers-as-legs metaphor. It uses walking gesture for precise and short distances, Segway gesture for travelling faster on the ground and surfing gesture for travelling long distances. This idea of using multiple locomotion techniques helped us develop a possible solution for travelling in complex VEs.

”Shake your head” technique uses head gestures for locomotion. Lateral head movement is used for walking, and the vertical head movement is used for jumping [160]. Compared to the joystick and mouse, this technique was found to be difficult to use and tiring, but the participants reported more fun, presence and walking realism. Walkabout[11] is a locomotion technique which turns around the users when they reach the boundary to navigate large VR environments, similar to redirected walking. Running in place (RIP)[12] uses a running in place natural gesture to navigate in VR, but the user has to keep the hand controllers near the hip while running in place.

2.1.5 Discussion

Vehicular locomotion mimics the steering experience in the real world and is effective when realistic vehicular locomotion is desired. However, vehicular locomotion almost always needs additional props to make the VR experience compelling. *Real Walking* is the most natural and effective way to locomote in VR. Previous user studies showed that walking in VR helps with spatial understanding [33, 183] and performs better in search [130] and exploration tasks [183]. Walking also increases presence [164, 183] and decreases cybersickness [33]. However, tracking space is a major constraint since users cannot walk in VE larger than the tracked space. *Redirected Walking* addresses this concern to a certain extent by redirecting the users to use limited tracked space for travelling a larger VEs [123]. Similar to real walking, RW is applicable for the spatial understanding [183] and obstacle avoidance tasks [130]. However, RW still needs a larger tracking space (12m x 44 m) and is not suitable for VR applications that have sudden acceleration or turns since that might lead to user crossing the tracking boundary [151].

Gait negation techniques such as omni-directional treadmills provide a way to walk naturally in a limited space. However, the cost of the hardware setup is high and prolonged use of these interfaces leads to physical

[11] *http://www.anbsoft.com/walkabout/*
[12] *http://smirkingcat.software/ripmotion/*

fatigue. *Partial gait technique* such as WIP are a possible alternative to real walking locomotion since it needs limited tracking space [175]. Since stepping gestures provides proprioceptive and vestibular cues, WIP has presence scores comparable to RW and low cybersickness scores [142]. WIP is a hands-free technique and has a better resemblance to real walking than vehicular or non-natural locomotion techniques. However, WIP gestures are perceived as strenuous and causes physical fatigue after prolonged use [107]. Another challenge in WIP is starting and stopping lag in detecting the walking gestures, and this results in unwanted collisions in VE especially in narrow spaces [44].

Artificial locomotion using joystick is a simple way to locomote in VR. However, it is well understood to induce cybersickness [22]. *Magical metaphors* such as Teleportation present a simple way to travel in VR, but sudden jumps in viewpoints lead to spatial disorientation [24].

Looking at previous literature, we see that no single locomotion technique is ideal, and each technique has drawbacks. Kruijff and Riecke [82] rated, from red (-3) to green (3), different locomotion techniques according to usability, naturalism/realism, effort, safety, cost and cues as shown in Figure 2.1. For an ideal locomotion technique, ratings for all the attributes would be green. To develop an ideal locomotion technique, we have to envisage its characteristics. To do that, we first discuss the human factors affecting locomotion in VR in this dissertation before listing the characteristics of an ideal locomotion technique.

2.2 Human Factors

To design locomotion techniques that enable maximum human performance during execution of a task, we need to understand the underlying human factors that influence the performance of the user. *Human factors* refers to the capabilities, characteristics, and limitations of the human user, and includes considerations related to the body (acting), the senses (perceiving) and the brain (thinking). Human factors analysis needs understanding of the true potential of a human being in performing a task. If we could develop locomotion techniques considering the true mental and physical potential of a user, the interface will be innovative, engaging and highly usable.

There are many human factors affecting VR experiences. In this dissertation, we assume that the key human factors affecting locomotion performance as comfort and usability.

2.2.1 Comfort

Comfort is absence of unease and pain, and it can be physical and psychological. In this dissertation we define comfort as lack of cybersickness and fatigue.

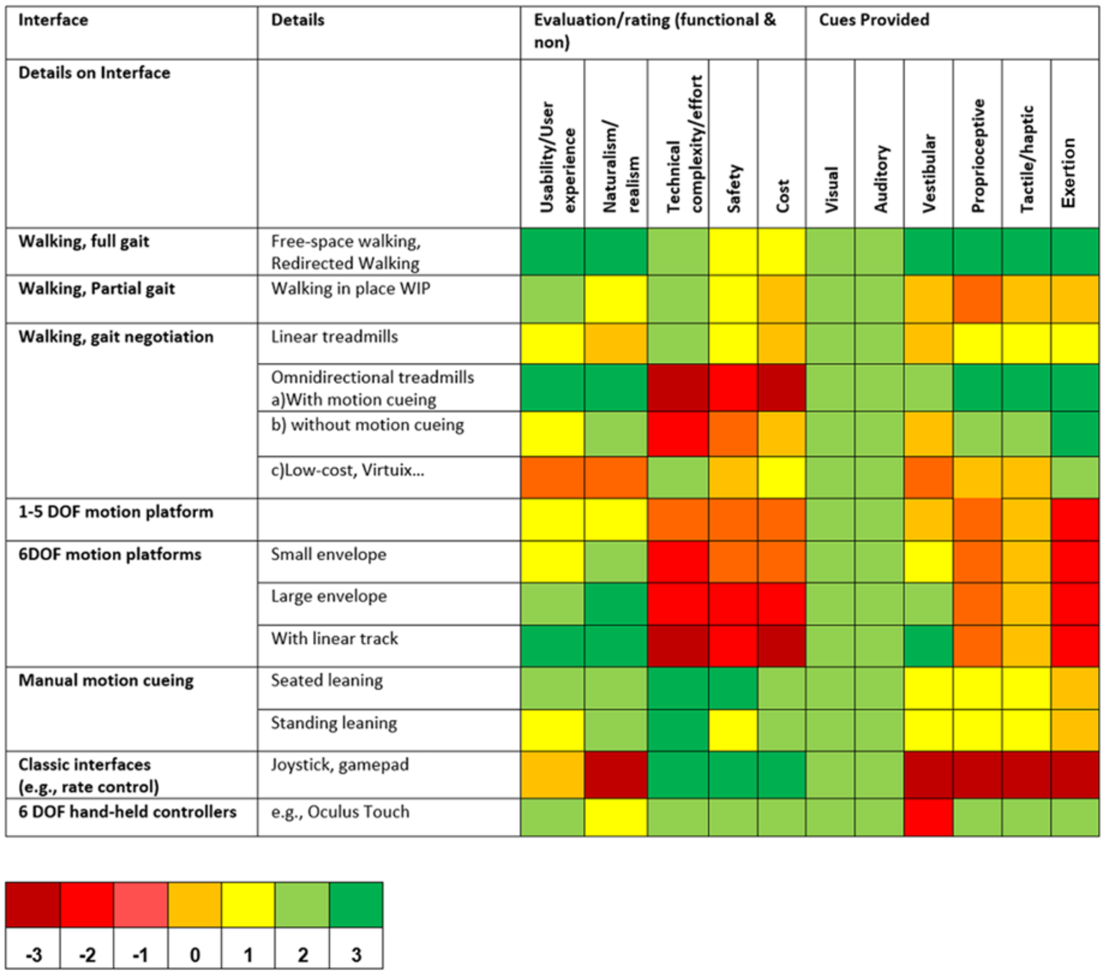


Figure 2.1: Locomotion Technique Ratings[82]

Cybersickness

Cybersickness is one of the most serious health and safety issues in VR. Frank Biocca asks whether it is "a snake in the public's virtual garden?" [10]. Given the hype of VR technology among both manufacturers and consumers, it is a reasonable question given the fact that 20-40 percent of users are affected by cybersickness [148]. The symptoms of cybersickness include eye strain, headache, pallor, sweating, disorientation, the fullness of stomach, vertigo, ataxia, nausea, and vomiting [89]. After-effects of cybersickness include illusory sensations such as moving, climbing and rotating, flashbacks, and reduction in motor control, all of which pose threats to the safety of users. Though the exact reasons for cybersickness are not yet known, one of the major causes is the illusion of self-motion (vection) [70, 89]. Though sensory conflict theory [115], the poison hypothesis [100] and postural instability theory [155, 3] attempt to explain cybersickness, the exact causes are not yet understood. Though motion sickness and cybersickness look similar, they have different etiologies. Vestibular stimulation [148] plays a major role in motion sickness and vision may play a smaller role, while in the case of cybersickness, visual simulation is enough to induce nausea even without vestibular simulation [148]. Symptoms vary with each person and the time period for the after-effects is known [148]. Some studies show reduced symptoms after repeated exposure, while other studies show the opposite [96]. In this dissertation, the aim is not to explain the etiology of cybersickness, but to explore the design techniques that avoid creating sickness in users.

Some of the contributing factors of cybersickness are as follows:

- **Display and Technical Issues**: A review by Rebenitsch and Owen [125] on cybersickness in applications and visual displays states the suspected application aspects that induce cybersickness. The review explains that field of view and navigation are strongly correlated to cybersickness. Imperfections of technology such as position tracking error [10], flicker [52], time lags [116], headset weight [173], and calibration issues are contributing factors.
- **User Characteristics**: Gender, age, illness, position in the simulator, and past individual experience may contribute to cybersickness [84]. Women are found to be more susceptible to sickness than men and one reason could be: women have a wider field of view than men [80]. Age can be an important factor for cybersickness [115]; users between 12 and 21 years old were found to be less susceptible than people older than 21. Any illness, fatigue, or medication can also be a contributing factor [47].

A technical report by Kolansinski [80] enumerates other possible contributing factors for simulator sickness. Failure to maintain calibration which in turn causes mismatch of user and visual movement in vehicle simulators, and virtual environment applications was one of the major cause of nausea [96]. Unlike pilots who are selected to attrition based on their resistance to sickness, the typical consumers of VE have a high probability of being victims of nausea. Users may also be under the influence of external medications, drugs or alcohol. Providing a perfect visual system without calibration issues or time lags was a possible solution, but this is not true since the conflicts between the sensory systems exist. An engineering solution which has the capability of removing the issue of cybersickness has not yet been found. Hence, one faction of the VR community has sought to solve the issue of motion in cybersickness by using metaphors such as Teleportation [24] and magic portals [150] for locomotion in VE. However, the instantaneous change in the user's view of VE using magic metaphors reduces presence in the VE.

Another way people have sought to combat cybersickness is to use subtle dynamic field of view (FOV) modifications, as suggested by Fernandes et al. [45]. The study indicates that the FOV restrictors (larger FOV while moving slow and smaller FOV while moving fast) helped participants to stay in VR longer and reduced discomfort. 'Nasum Virtualis' [13] is another simple technique for reducing cybersickness. The perception of

[13] $http://www.purdue.edu/newsroom/releases/2015/Q1/virtual-nose-may-reduce-simulator-sickness-in-video-games.html$

motion sickness is less intense when user's view has fixed visual reference objects compared to moving objects. Using the same concept, this technique inserts an image of a virtual nose on the user, reducing the cybersickness.

Natural walking-based locomotion techniques address the issue of cybersickness well, but they have other issues such as drifts: WIP causes positional drift in user even though the user aims to make stepping-in-place gestures to travel in VE [108], safety, costs of the equipment, cognitive load, etc. An interface that can induce a sense of real locomotion without placing high cognitive loads on the user and reducing cybersickness in most users would be a great solution to the stated issues. The active process of self-motion perception relies on prediction (of how the incoming sensory information will change because of the person's actions) and feedback. Locomotion interfaces should maintain such a feedback loop with the user. Using virtual rather than physical rotation, subjects reported symptoms of cybersickness [88].

Ang and Quarles [2] developed GingerVr, an open source repository of cybersickness reduction techniques in Unity. Primary strategies to reduce cybersickness include:

- Adding platforms to simulate locomotion in VE to reduce vestibular and visual cue conflicts is one of the best solutions. Motion platforms such as Virtuix Omni, treadmill, and stepper platforms were known for reducing cybersickness [88].
- Direct vestibular stimulator: Recent developments in Galvanic Vestibular Stimulation (GVS) [95] hold a promising solution for cybersickness, but they still need to be tested among a greater population.
- Introducing adaptation programs to VE was reported to help users experience VE comfortably [128], but the user must be willing to put forward some time to go through the adaptation process. Reducing the exposure of users to VE until they are adapted is a better solution.
- Maneuvering at higher speed and rotation was found to increase cybersickness [96] and hence, as a part of the design, it is a good idea to minimize the tasks which need high linear or rotational maneuvering.
- Introducing an interface to detect (heart rate or skin conductance sensors) if the users are prone to sickness and giving appropriate adaptation can be one of the solutions for reducing the discomfort to the users.
- Global visual flow, which is the ratio of the observer's velocity and eye height, is reported as a contributing factor. Hence, minimizing the speed at the higher altitudes can minimize sickness [96].
- Freedom of movement and level of control can be a possible factor in manipulating the perception of motion sickness though its role is not yet understood completely [41]. Anticipating the direction of motion can lower the sensory mismatch. For example, a passenger in car is more susceptible to motion sickness than the driver of the car since the driver has control over the motion. Giving control to the user in VE can be a possible solution as a study by Stanney and Hash [147] suggest the reduction in cybersickness in similar conditions. Venkatakrishnan et al. [167] conducted an driving simulation experiment to study the effect of motion control on cybersickness. They found that participants in the driving condition experienced higher levels of cybersickness than participants in yoked pair conditions.

These results contradict the conclusion from other studies discussed above, hence more research needs to be done on fidelity of control metaphor's feedback.

- Changing or restricting the FOV of the user has proved to reduce the cybersickness significantly [45].
- Introducing a virtual nose can also reduce cybersickness since it gives a fixed frame. of reference.

Cybersickness in VR user can be measured using objective or subjective measures [170]. We can use the objective measures such as heart rate [105], skin conductance at the forehead [49], and respiration rate [76]. The subjective measures include multi-item questionnaire such as the Simulator Sickness Questionnaire [71], Short Symptoms Checklist [106] and Fast Motion Sickness Scale [73]. In our user studies, to measure perceived simulator sickness, we use the previously validated Simulator Sickness Questionnaire by Kennedy et al. [71]. SSQ consists of three sub-scales (oculomotor discomfort, disorientation, and nausea) on a four-point scale.
. The questionnaire discussed above detects onset of cybersickness post-experiment. Islam [59] developed a deep learning based framework for detecting the cybersickness and then applying the cybersickness reduction techniques in real time to ease the discomfort. Padmanaban et al. [114] developed a machine learning approach to predict cybersickness in 360 degree stereoscopic videos. However, the algorithm needs to be tested on a large generalised data to conclude that the prediction works.

Fatigue

Fatigue is another factor in comfort of the users. In relation to locomotion, fatigue has two dimensions: physical and psychological. In reference to physical ergonomics, comfort refers to the ability of a user to maintain a pose for a prolonged time. Fatigue is experienced by the user when the muscle load tolerance is surpassed [22]. Physical fatigue can also occur due to prolonged repetitive use of muscles. Fatigue can occur in the shoulder, back, arms, wrists, and legs. In locomotion interfaces, the common occurrence of physical fatigue is due to walking or performing walking gestures for longer times. However, when the user uses controllers or any other device, prolonged duration of holding the device or repetitive gestures (triggering using the fingers multiple times) may lead to finger fatigue.

Cognition is a key aspect of user interaction as it processes the perceived stimuli. Cognition helps in generating and using the knowledge perceived by other senses. Cognitive load or mental load is the amount of mental work or effort required to complete a task or a goal and is an important factor in mental or psychological fatigue [168]. Mental fatigue can also be caused due to user's errors in task performance and prolonged task performance time [113]. We use the NASA-TLX workload questionnaire to find the subjective workload (including physical and mental fatigue) in our user studies [51].

2.2.2 Usability

The official ISO 9241-11 definition of usability is: ”the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, satisfaction in a specified context of use.” To measure subjective feelings of usability, we adopted previously validated System Usability Scale (SUS) [25].

2.3 Characteristics of an Ideal Locomotion technique

Looking into the literature on locomotion techniques discussed in sections above, human factors and the assumptions, the characteristics of an ideal locomotion technique are listed below. We note that the characteristics of a ideal locomotion technique differs based on a application. There is no condition that an ideal locomotion technique for a particular VR application has to include all the characteristics that are listed below.

- **Comfort**- An ideal locomotion technique should induce minimal perception of Cybersickness and induce minimal fatigue even after prolonged use.
- **Presence**- An ideal locomotion technique should enhance the presence of the user in Virtual Environment.
- **Accuracy**- Accuracy is used to measure the user’s performance. The degree of accuracy depends on the deviation of the user from the ideal path. The deviation from the ideal path might also result in collisions with the objects and hence a measure of accuracy. An ideal locomotion technique should enhance user’s accuracy in completing the tasks if the VR application requires accurate navigation (for example, avoid obstacles).
- **Speed**- Speed is measured by how fast the user reaches the target destination. An ideal locomotion technique should be efficient (Faster according to task and environment). For example, it is not ideal to use walking, if the target location is very far from the starting point. A locomotion technique that uses a steering metaphor (Joystick) or magical metaphor (Teleportation) can be used in this case.
- **Smooth movement**- Smooth movement is a measurement of smoothness in a movement without abrupt jumps or jerks. For example, if a WIP makes the user stop as soon as the foot is down, the user feels a sudden stop. An easy-in or ease-out approach would be a smoother transition from a movement to stop phase and vice-versa. An ideal locomotion technique should have smooth movement unless the VR application has jumps as part of the experience. This characteristic doesn’t necessarily limit the head oscillations included in the camera to improve realism similar to Lecuyer et al. [90].
- **Learnability**- Learnability is the ability to learn the interface quickly and efficiently. An ideal locomotion technique should be easy to learn.
- **Real world transfer**- This is more applicable for virtual training simulations. It is the measure of how well a user can perform the real-world task based on the training in the virtual world. This characteristic is especially applicable to the VR applications that train user for a specific skill that has to be used in reality.

Some of these characteristics might look like they are inherently in tension. For example, Teleportation causes less discomfort and has high speed, it is not ideal for real-world transfer of skills and presence. However, studies [24] shows that if the VE has less complexity, then Teleportation doesn't significantly reduce the presence. Hence, Teleportation would be suitable for VR application that has VE with less complexity, and that requires high speed. These characteristics are guidelines for developing or choosing a right locomotion technique based on the requirements of VR application and there is no condition that a locomotion technique should have all of the characteristics.

Summary

This chapter discusses locomotion in VR and its previous literature. In section 2.1, we classified locomotion techniques based on their naturalness and organised the previous literature accordingly. In section 2.2, we further discussed Human factors relevant to locomotion in VR. Finally, we listed the characteristics of an ideal locomotion technique. Keeping the characteristics of an ideal locomotion technique as context, we developed *TriggerWalking*, a novel Bio-mechanically inspired locomotion Technique that is discussed in detail in the next chapter.

Chapter 3

The TriggerWalking Locomotion Interface

In the previous chapter, we discussed the locomotion techniques previously implemented, human factors affecting locomotion in VR and the characteristics of an ideal locomotion technique. In this chapter, we discuss the implementation and evaluation of a novel comfortable and usable locomotion technique TriggerWalking and its evaluation.

Introduction

Moving through a computer-generated three-dimensional (3D) environment is one of the essential tasks in virtual reality (VR) applications [129]. By far, the most basic and natural form of active human travel is bipedal walking [153]. Hence, natural locomotion user interfaces (LUIs) based on real walking in Virtual Environments (VEs) support a veridical model of reality and have been proven to be effective for many applications, such as training, rehabilitation, and entertainment [131, 129]. However, a one-to-one mapping between real and virtual motions is often not possible due to the physical constraints of the tracking space.

Hence, virtual travel methods such as Teleportation [24] that allow users to jump long distances at once are particularly useful for moving in larger spaces, but have been shown to reduce the sense of presence, spatial awareness, and spatial cognition [21]. Artificial locomotion techniques, such as Joystick, are known to induce motion sickness and nausea due to sensory conflict [89]. Techniques such as Walking-in-Place (WIP) movement use physical gestures, such as walking or running in place [44, 143], and arm swinging to control camera motion [180], and they provide near-natural walking experiences, and, since users have physical control over their motion, they reduce nausea [41, 89]. However, repetitive physical motions based on leg or arm movements induce fatigue after prolonged use. An ideal locomotion technique has to be as simple and easy to learn as artificial locomotion (for example, Joystick) and Teleportation, but has to increase the illusion of presence similar to natural or semi-natural locomotion techniques. Besides, the ideal locomotion techniques must be comfortable, i.e, induce no cybersickness and fatigue. This chapter introduces and explores TriggerWalking, a bio-mechanically inspired LUI that is easy to learn, comfortable, presence enhancing and efficient.

Chapter Roadmap

In this chapter, we introduce the physical and visual aspects of walking and relate them to the design of a novel locomotion technique, TriggerWalking. This chapter also describes a series of user studies conducted to evaluate the locomotion technique. The chapter has the following sections:

1. **Analysis of HMD Oscillations**
   To simulate a realistic VR walking sensation, we did a kinematic analysis of head oscillations. The aim was to analyze the head oscillation when users wore HMD and reintroduce the head oscillation information back to the LUI.
2. **TriggerWalking**
   TriggerWalking is a bio-mechanically inspired LUI which is comfortable and has high usability. This section explains its implementation and a user study to evaluate comfort and usability.
3. **Comparing TriggerWalking to other locomotion techniques**
   This section compares and evaluates TriggerWalking to popular locomotion techniques Joystick, Walking-in-Place, and Teleportation, and reports the result in detail.
4. **Evaluating and comparing game-controller based LUIs**
   The section explains the user study conducted to compare and evaluate TriggerWalking to game-based locomotion techniques Joystick and Speedpad. The results are further analyzed and discussed in detail in the section.

3.1 Analyses of HMD Oscillations

Studies have shown that a passenger in a car experiences fewer symptoms of motion sickness when asked to drive the car, rather than be a passenger in the car [41]. Anticipating and/or having control over movement plays a major role in the comfort of users [89]. During walking in the real world, vestibular, proprioceptive, and efferent copy signals, as well as visual information, create a consistent multi-sensory representation of a person's self-motion, i.e., acceleration, speed, and walking direction [78].

Walking is a multi-sensory experience, but similar walking sensations can be achieved, for example, by adding artificial camera motions to reflect optical flow similar to natural oscillations of the body and head during walking [90]. The head oscillations are caused by the bipedal style of human walking, in which the body's centre of mass displaces in the lateral, vertical, and fore-aft directions [1]. In order to reflect these bio-mechanics of real walking in video games, the viewpoint of the gamer can be slightly dynamically modified during virtual walking. The resulting motions of the camera are used to increase the sensation of walking, but can also provide other cues, such as the mental or physical state of the avatar (illness, fatigue, etc.) [162]. For example, games such as "Bioshock"[1], "Half-Life"[2], and "Brothers in Arms: Road to Hill 30"[3], move the camera in oscillating motions along the vertical and horizontal axes with a small amplitude. Previous work has compared head oscillations along x, y, and z axes in first-person camera movements in desktop-like environments with seated users [90, 39, 14]. The results indicate that vertical and lateral translations were selected by subjects to be closest to natural movement, and they also improve spatial cognition in travel distance estimation.

While there is a vast body of literature about human walking, in particular, regarding displacements of the body's centre of mass as well as the head, not much attention has been given to head oscillations while users walk wearing an HMD. However, it is known that the physical properties of HMDs slightly modify the bio-mechanics of walking when users are wearing an HMD. For instance, Janeh et al. [66] and Mohler [99] found that when users walk with an HMD, most gait parameters (i.e., walking velocity, step count, step length, base of support time, and double support time) significantly vary from the corresponding walking parameters in the real world and it is essential to consider these differences when developing realistic VR camera motions for LUIs.

To provide a realistic VR walking sensation for a bio-mechanically inspired LUI, we performed a kinematic analysis of head oscillations when users walk wearing an HMD. For the simulation of head oscillations, we focused on translational displacements along x, y, and z axes only, since visual rotations which deviate from the actual head rotations are known to induce severe cybersickness and should be avoided [45].

3.1.1 Materials and Methods

The experiment took place in a 7m×5m laboratory room (see Figure 3.1). Participants wore an HTC Vive HMD, which provides a resolution of 1080×1200 pixels per eye, an approximately 110° diagonal field of view, and a refresh rate of 90Hz. Positional tracking was implemented using the lighthouse tracking system with an available walking space of approximately 3.5m×3.5m. In order to provide a realistic VR scenario, participants held the Vive controllers in their hands while walking. Using a similar method as proposed by Steed [149], we measured an end-to-end latency of approximately 25ms between physical movements and visual response. For rendering, system control, and logging, we used a computer with an Intel Core i7-6700 processor, 16GB of main memory, and an NVIDIA GeForce GTX 1080 graphics card. The VE was rendered using the Unity3D engine version 5.4 and showed a simplified outdoor scene with a straight path (see Figure 3.1 (inset)).

[1] http://www.bioshock2game.com
[2] http://www.sierra.com/
[3] http://store.steampowered.com/app/15190

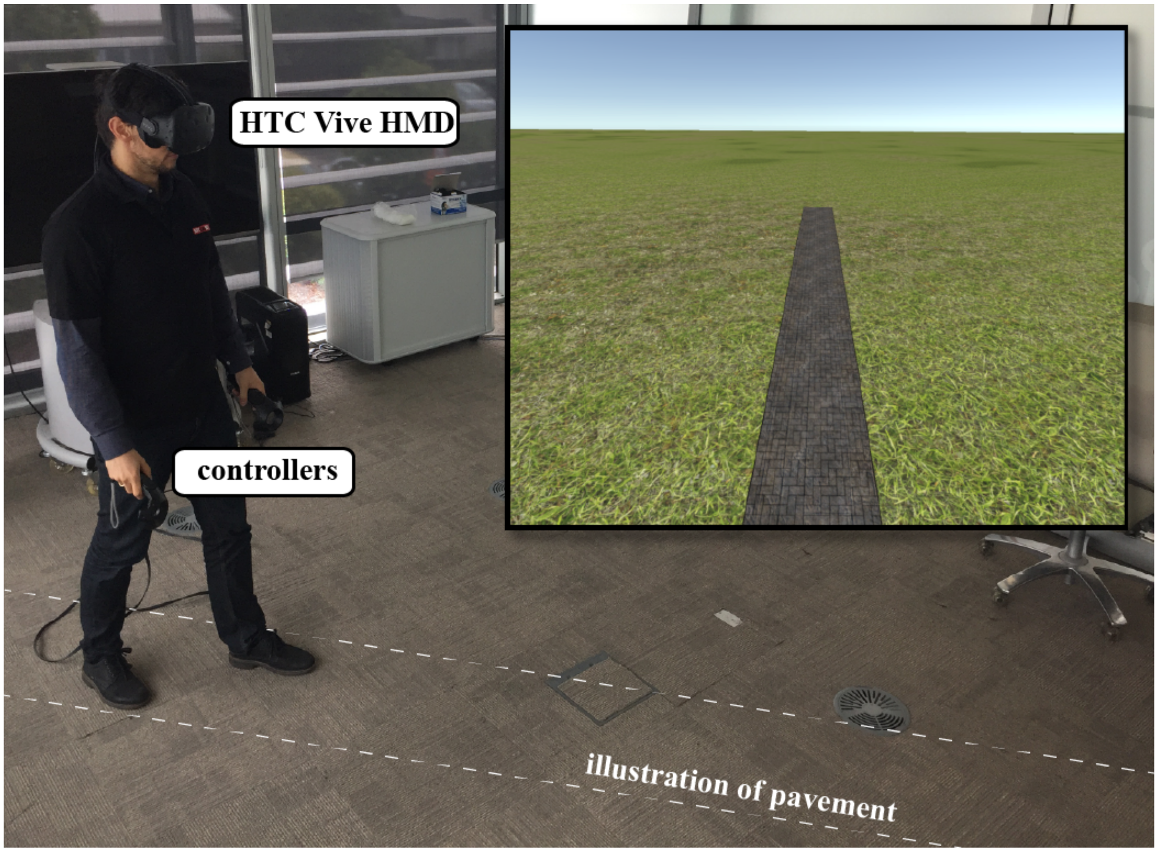


Figure 3.1: Images from the experimental setup for the analysis of HMD oscillations. The inset shows the participant's view of the VE.

Procedure

The experiment was approved by the Human Ethics Committee, University of Canterbury. Before the experiment, all participants filled out a demographic questionnaire and received detailed instructions. Then, they were asked to wear the HMD and were trained to perform the experimental task. The task was to walk along the pavement in the VE 12 times using their average walking speed. The pavement was 90cm wide and about 15m long. They were instructed to take three complete steps, allowing us to record a full gait cycle for each leg from the start to the stop phase. After each walk, the participants rotated 180°, and the next trial started. Participants were instructed to alternatively start with their dominant and non-dominant leg, which we measured using the lateral preference inventory [38]. During each walk, we measured the head position at each frame. The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was 20 minutes. Participants were allowed to take breaks at any time between trials.

Participants

Thirteen participants (three female, nine male, one other), aged 24–39 (M = 28.1, SD = 4.86) participated and completed the experiment. The participants were students or members of our lab. All participants had a normal or corrected-to-normal vision. Participant height varied between 162cm–186cm (M = 171.9, SD = 8.29). According to the lateral preference inventory, for handedness we found that eleven participants were right-handed, one was left-handed, and one ambidextrous, while for foot dominance the results showed that eight participants were right-foot dominant and five were left-foot dominant.

Data Analysis

For the analysis, we considered only those samples (i. e., HMD positions in (x,y,z)), which were part of each gait cycle. Therefore, we removed the samples at the start and end of each walk where participants rotated and prepared for the next walk. Furthermore, we excluded one data-set since the participant's path deviated from the pavement.

We first calculated a linear fit to the samples to extract the actual walk direction for each walk. To measure the vertical displacements (y-axis) along the walking direction, we calculated the difference between the minimum and maximum y values of the HMD. For the fore-aft deviation, we measured the differences between all subsequent samples along the walk direction. For all these differences, we calculated the standard deviation from the mean again.

3.1.2 Results

The results show that the mean deviations for vertical displacements varied between participants from 4.4cm–13.8cm (M = 8.7, SD = 3.29), lateral displacements varied between 3.91cm–7.68cm (M = 5.5, SD = 1.13), and fore-aft displacements between 1.56cm–3.83cm (M = 2.8, SD = 0.56).

The average speed per participant varied between 0.4m/s–1.1m/s (M = 0.7, SD = 0.19), which is significantly slower compared to the average speed of walking (1.4m/s) in the real world. The results show a strong correlation between body height and walking speed (r = 0.85), and a moderate correlation between body height and vertical displacement (r = 0.43). The displacement corresponds to 5% of the user's body height.

3.1.3 Discussion and Implications

The results show that the HMD oscillations we found are comparable to those reported in the literature for human walking without HMDs, though the walking speed was significantly lower than in the real world. For example, Pozzo et al. [122] found displacements along the vertical axis of 5cm-16cm depending on the walking speed. Similar magnitudes have been reported for lateral and fore-aft displacements, while most results have been measured on treadmills, which typically results in smaller head oscillations [122, 54]. Our speed results are also in line with results reported by Mohler [99], showing a decrease in walking speed when users wore an HMD (mean = 1.26m/s, SD = 0.77) compared to walking without an HMD.

The average speed of our participants was even slower than the speed reported by Mohler [99], which might be due to the fact that our participants walked within a room-scale set up in contrast to the much larger space ($180m^2$) used by Mohler [99]. With our results, we used MATLAB curve fitting tool to approximate camera oscillations of an HMD user similar to the equations suggested in [90, 14]:

$$D_V = A_V \cdot \left(\frac{\cos(2 \cdot \pi \cdot T) - 1}{2} \right) \tag{3.1}$$

$$D_L = A_L \cdot \cos(\pi \cdot T) \tag{3.2}$$

$$D_F = A_F \cdot \cos\left(2 \cdot \pi \cdot T + \frac{\pi}{2}\right) \tag{3.3}$$

where D_V, D_L, and D_F denote camera displacement in the Vertical, Lateral, and Fore-aft directions of space, T is the time, and A_V=0.05 $\cdot$ user height, A_L=5.74cm, and A_F=2.84cm are the three mean amplitudes of the corresponding oscillating motions found in our analyses. The frequency of steps (F), together with the stride length (S), define the walking velocity (V):

$$V = S \cdot F \tag{3.4}$$

Our primary goal is to develop an LUI to support the characteristics of the bio-mechanics of real walking without the requirement of performing physical movements with the legs. Despite the requirement for near-natural walking, the design of such a bio-mechanically inspired LUI is driven by the need for efficient LUIs to (1) add little extra physical work for the user, (2) be expressive enough to accomplish multiple types of movement (e. g., precise, short-distance movements, as well as efficient, long-distance movements, and backward/strafe movements), and (3) take advantage of common, general-purpose interface devices. Keeping these characteristics in mind, we developed a bio-mechanically inspired LUI called TriggerWalking.

3.2 Bio-mechanically Inspired LUI

The idea of TriggerWalking is to virtually control the gait cycle in the VE using the triggers in combination with the orientation of the VR controllers and HMD. Our approach was inspired by the observation that people can easily mimic walking motions with their fingers [74, 182]. Furthermore, users can perform constant isometric fatiguing exercises with the index finger for approximately one minute before significant decreases inaccurate force production occur [46]. Hence, we use the concept from natural walking of taking steps to reach a destination, but replace the legs with the triggers of common VR controllers. As illustrated in Figure 3.2, a controller is held in each hand in the natural grip, and the arms are allowed to relax either on the legs when the user is seated or at the sides of the user when standing. In these poses, users are expending

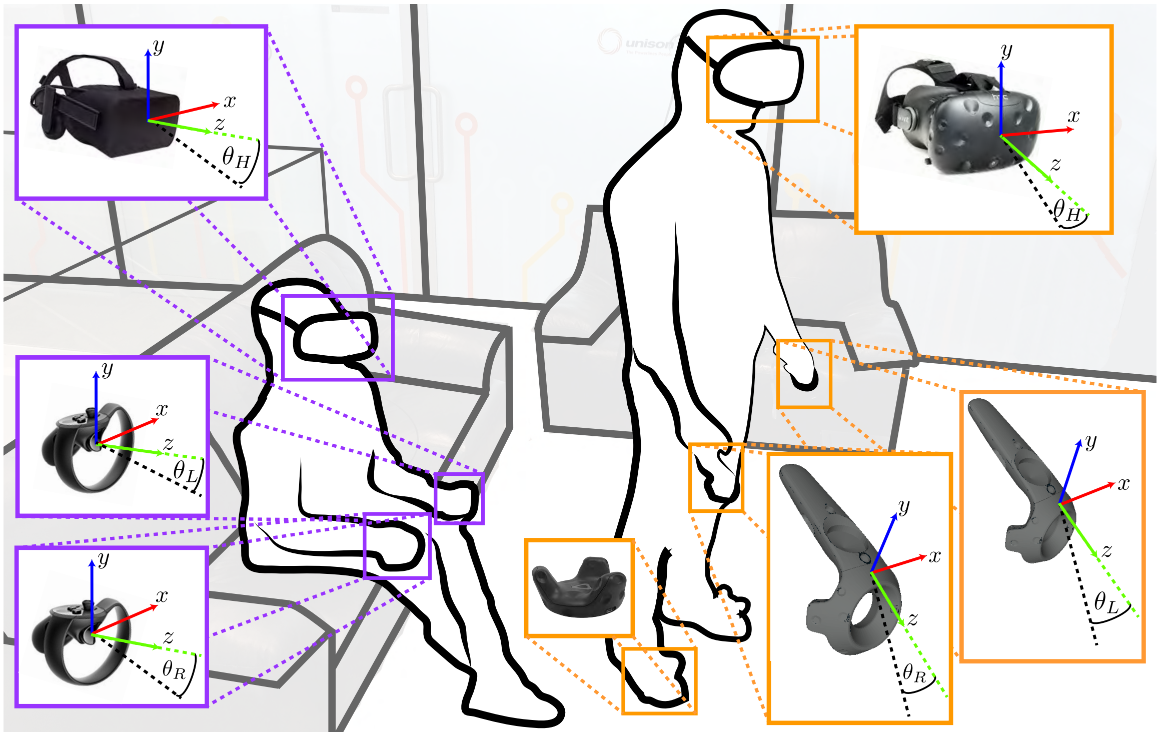


Figure 3.2: Illustration of the different use cases for our technique: a left person uses the technique while sitting with an Oculus Rift display and touch controllers, whereas the right person uses the technique while standing upright with an HTC Vive display and controllers. The insets show the controller, displays and corresponding angles used for the direction, and speed calculation.

minimal energy and have the triggers close to the legs. Controller tilt in the *y*-axis controls the left and right step length, whereas the number and frequency of trigger pull to control the speed of the gait cycle. The main components of TriggerWalking implementation are explained below.

3.2.1 Head Oscillation

To provide a realistic VR walking sensation for TriggerWalking, we included head oscillations when users walk with an HMD.

Types of Camera Oscillation

In order to differentiate between the most often observed combinations of vertical, lateral, and fore-aft camera oscillations, we defined the following types:

- *None* (N) means that no camera oscillations are applied during walking.

Table 3.1: Types of Camera Oscillations

Type of Camera Oscillations	D_X	D_Y	D_Z
None ($\cdot$)			
Vertical ($\updownarrow$)		✓	
Lateral and Vertical ($\leftrightarrow + \updownarrow$)	✓	✓	
Fore-aft, Lateral, and Vertical ($\odot + \updownarrow + \leftrightarrow$)	✓	✓	✓

- *Vertical* (V) means that only D_Y from Equation (3.1) is used,
- *Lateral and Vertical* (L) means that both D_X and D_Y are used (cf. Equations (3.1 and 3.2)), and
- *Fore-aft, Lateral, and Vertical* (F) describes head oscillations produced by D_X, D_Y, and D_Z (cf. Equations (3.1–3.3)).

Triggered Camera Oscillations

By pulling the trigger, the user controls the current position in the gait cycle, which in turn defines the oscillations to be applied to the virtual camera. In its initial state, the trigger data equals 0, whereas a fully pulled trigger sends 1; in between, a corresponding float value is returned, and the distance travelled in each partial step depends on the float value of the amount of trigger pulled. There is no requirement for alternating trigger pulls (left/right). If a user pulls the same trigger twice, it is analogous to taking two steps with the same foot.

3.2.2 Velocity Control

Walking velocity can be controlled by an increased stepping frequency or an increased step length [153].

Trigger Frequency

Assuming constant step length, an increased frequency (F in Equation (3.4)) results in increased movement velocity. While the amplitude of the trigger pull does not affect the walking velocity, it changes the stride length and therefore the amount of camera oscillation; larger amplitudes cause larger oscillations, and smaller amplitudes result in smaller oscillations (cf. Equations (3.1-3.3)). Though this is a straightforward, biomechanically inspired approach for defining the velocity, it might lead to finger fatigue [140], in particular, when using high frequencies (e.g., rapid pulling of triggers) for longer periods of time.

Controller Orientation

The step length can be manipulated using the angle α of the controllers to the xz ground plane (cf. Figure 3.2). The speed can be increased by either increasing the trigger frequency (trigger-pull rate) or by changing stride length by changing the tilt angle of the controllers. Speed is scaled between 0.7m/s and 2m/s for tilt angles between 0 degrees (arms and hands hanging down at rest) and 90 degrees (forearms and controllers at right

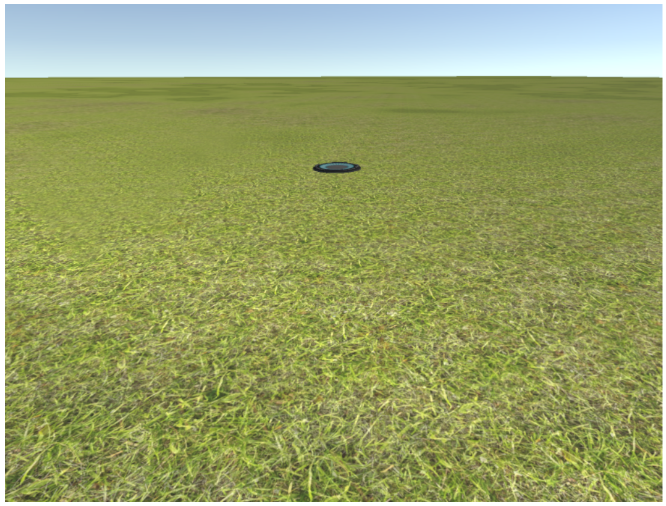


Figure 3.3: Participant's view during the experiment showing a target at an approximate distance of 15m.

angles to body). As illustrated in Figure 3.2, in the neutral or comfortable position, the angle α between the xz-plane and the y-axis of the controller is around 30°. For a given α, the step length S can be scaled by $\alpha + 10$ multiplied by the user's body height, resulting in a typical ratio between body height and step length [122, 54]. Hence, $\alpha = 30°$ results in an average velocity of about 0.7m/s assuming a corresponding step frequency of ca. 1Hz, whereas $\alpha = 90°$ results in the maximum S, which equals the user's body height.

3.2.3 Direction Control

We implemented three ways of controlling the direction of walking, using either a single controller, both controllers, or HMD view orientation (see Figure 3.2). In a pre-test, we found that using two controllers was most intuitive in the situation that users were equipped with a controller in each hand. In general, travel is not the primary task in a virtual experience, and if there is a secondary task (e.g., shooting targets) that needs one controller, the single controller mode can be used in those cases. When two controllers are needed for the primary task, the user could implicitly invoke TriggerWalking only when the arms are in the rest position, and otherwise use the triggers for something else (e.g., pointing with a raised arm).

3.3 Experiment

We performed an experiment to evaluate the TriggerWalking technique and its bio-mechanical approaches described above in terms of task performance as well as spatial cognition. We measured the participants' distance and orientation judgments for each of the four different types of head oscillations using a triangle completion task. As part of the experiment, participants had to complete a triangle by pointing to the starting point after they virtually walked along two edges of a triangle [68]. This triangulated pointing method has the advantage of allowing participants to perform spatial reasoning with the simplest nontrivial combination of translations and rotations as often observed in spatial cognition experiments [68, 126].

3.3.1 Materials

The experiment took place using the same system setup as the analyses of HMD oscillations described earlier. As illustrated in Figure 3.3, the VE was rendered using the Unity3D engine and showed a simplified outdoor scene with two different targets displayed on the ground. Depending on the condition, after reaching the first target, the second target was displayed 90° to the right or left. We specifically chose a simple scene that did not provide any significant landmarks other than targets that might either distract the participants or give them additional cues about their location and travelled distances. However, the ground texture provided sufficient optic flow information for participants to estimate their motions when moving through the VE. Similar VEs have been used for several distance and motion perception experiments [126, 68].

3.3.2 Procedure

Before the experiment, which was approved by our University of Canterbury, Human Ethics Committee, all participants filled out an informed consent form and received detailed instructions and training on how to perform the experimental task. For each trial, participants were instructed to virtually navigate towards two target circles using one of the four different types of head oscillations described above.

The positions of the targets were randomly calculated in such a way that each position was used only once for each type of head oscillation. Half of the 18 targets were displayed to the left and the other half to the right along an orthogonal direction from the first walking direction. The arrangement of the right half of the targets is illustrated in Figure 3.4. At first, participants were instructed to virtually navigate towards the first target circle (*intermediate target*), which was displayed at distances of 5m, 10m, or 15m on the ground in a randomized orientation around the user (see Figure 3.4). We decided to use 5m since this is about the limit of today's room-scale tracking environments in which a user can naturally walk without requiring additional LUIs.

After they were within a 0.5m radius of the target, an arrow displayed at eye height showed the direction towards the next target (*final target*), which was either displayed 90° to the left or right. Participants had to walk from the intermediate target (to the right or left) towards that final target, which was displayed again at distances of 5m, 10m, or 15m perpendicular from the initial walking direction. When they were within a 0.5m radius of the final target, they received an instruction to complete the triangle by pointing with their controller to their original start position, i.e., the location on the ground where they estimated the start location to be. For pointing, we displayed a virtual ray in the VE, which was attached to the VR controller in the dominant hand of the participants. After participants had a good estimation of the original starting position, they pointed the virtual ray to the starting point and confirmed the estimation with a button press using the second controller in

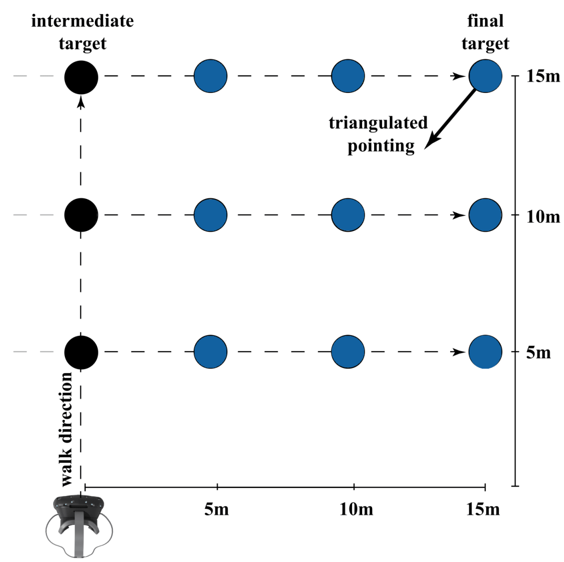


Figure 3.4: Illustration of the configuration of the half of the targets on the right. Intermediate targets are shaded black, and final targets are shaded in blue

the non-dominant hand to prevent unintended jittering. Neither the actual start point nor the intermediate targets were visible during the pointing phase. After participants finished their estimation, the screen went black, and the next trial started in a new randomized direction. We used 18 different target positions overall, to which participants had to walk virtually. Half of the targets to the right are illustrated in Figure 3.4.

Instructions were displayed in the HMD. In order to focus participants on the tasks, we did not communicate with the participant during the experiment after the initial training phase, during which we ensured that participants correctly understood the task. Participants wore noise-cancelling headphones to cover any ambient noise in the lab (HMD had no inbuilt headphones).

3.3.3 Measures

Using the described triangulated pointing method, we analyzed spatial cognition by measuring the angular accuracy of the pointing as well as the accuracy of the distance judgment. Finally, we measured the time the participants required for each trial (i.e., time is taken to reach the final target from the starting point). However, participants were instructed to solve the tasks with a focus on precise execution and were allowed to take breaks at any time between trials. We collected demographic information with a questionnaire before the experiment and measured the participants' sense of presence with the Igroup Presence Questionnaire [136], the perceived workload using the NASA Task Load Index (NASA-TLX), as well as simulator sickness with the Kennedy-Lane SSQ [71] before and after the experiment.

3.3.4 Methods

We followed repeated measures, within-subjects design, and tested four different head oscillation conditions, N, V, L, and F, as described in Table 3.1. The four different head oscillation conditions were balanced using a Latin Squared design with 24 different arrangements. For each head oscillation, we considered as independent variables overall 2×9 target locations as illustrated in Figure 3.4. The dependent variables were the time required to reach the intermediate and final positions, as well as the distance and orientation estimates.

After each oscillation condition with 18 trials, participants had to indicate their *discomfort score* [45] in the VR, using a virtual slider from 0 (indicating how they felt before the experiment) to 10 (indicating that they wanted to abort the experiment). Similarly, we measured their sense of being in a computer-generated world from 0 (indicating not at all) to 10 (very much) [136]. These simple questions are good estimates of the overall cybersickness and sense of presence, respectively [136, 45]. Finally, participants were required to estimate how realistic they perceived the walking simulation to be on a scale from 0 (very unrealistic) to 10 (very realistic). We used this approach of asking questionnaires in VR as we wanted to avoid lengthy interruptions during the experiment (due to taking off the HMD and answering the questionnaire on a desktop computer or paper), but still wanted to gather this crucial data. In summary, each participant completed 4 (oscillation type) $\times$ 2 (left/right turn) $\times$ 9 (target) = 72 trials, as well as 5 training trials, which were excluded from the analysis.

Hypotheses

Considering previous results in the literature regarding underestimation of distances [121], our hypotheses were as follows:

- **H1** Participants will underestimate travelled distance with TriggerWalking in all conditions.
- **H2** Participants will significantly improve their performance with TriggerWalking across trials.
- **H3** Simulated realistic head oscillations (conditions V, L, and F) will reduce errors in spatial judgments compared to no simulated head oscillations (condition N).
- **H4** Simulated realistic head oscillations (conditions V, L, and F) will increase the perceived realism of walking motions compared to no simulated head oscillations (condition N).

Participants

A total of 24 participants (10 female, 14 male) aged 19-34, (M=26) completed the experiment. The participants were students or members of our lab. All participants had a normal or corrected-to-normal vision. One of our participants reported a disorder of equilibrium, and one reported strong right eye dominance. The body height of the participants varied between 1.52-1.87m (M=1.7m, SD=0.09m). The total time per participant was 60 minutes, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing. Participants wore the HMD for approximately 45 minutes. They were allowed to take breaks at any time between trials. From a total of 1728 trials, 98 were outliers in spatial orientation estimates, and 66 were outliers in distance estimation, with an overlap of 6 trials. Hence, a total of 158 outliers in spatial orientation estimates and distance estimation were eliminated.

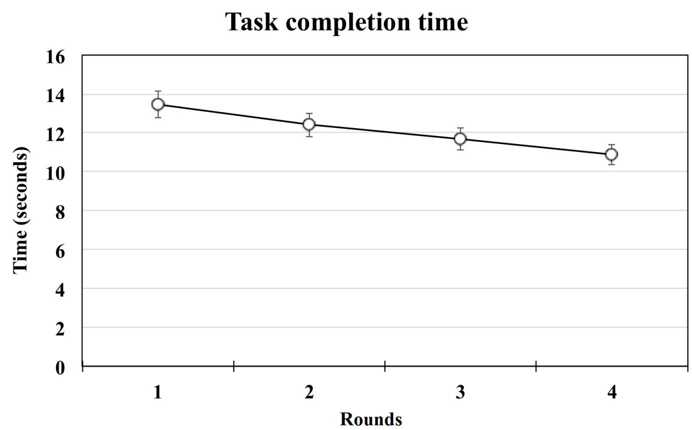


Figure 3.5: Results for time to complete the task for the different rounds with standard error bars, independent of the presented oscillation type.

3.3.5 Results

The within-subject data was analysed using repeated-measures GLM with oscillation-type as the factor.

Spatial Cognition

On average, the participants made an absolute error of 29.4° (SE=1.18) for condition N, 30.3° (SE=1.24) for condition V, 30.8° (SD=1.19) for condition L, and 31.1° (SE=1.16) for condition F. On average, participants exhibited absolute errors in distance estimation of 4.0m (SE = 0.14) for condition N, 3.9m (SE = 0.13) for condition V, 4.5m (SE = 0.15) for condition L, and 4.0m (SE = 0.15) for condition F. In terms of time, on average, participants required 11.8s (SE = 3.87) to reach the final target for condition N, 12.7s (SE = 5.88) for condition V, 12.9m (SE = 8.14) for condition L, and 12.3s (SE = 3.89) for condition F. We analysed the within-subjects data using repeated-measures general linear model (GLM) with oscillation-type as the only factor (four levels). The analysis did not yield any significant results for the absolute error in angle estimation ($F(3,69) = 0.074$, $p = 0.974$), errors in distance estimation ($F(3,69) = 1.563$, p=0.206), or time ($F(2.057,47.315) = 1.722$, $p = 0.189$) using a Greenhouse-Geisser correction. **Hence, hypothesis H3 could not be supported.**

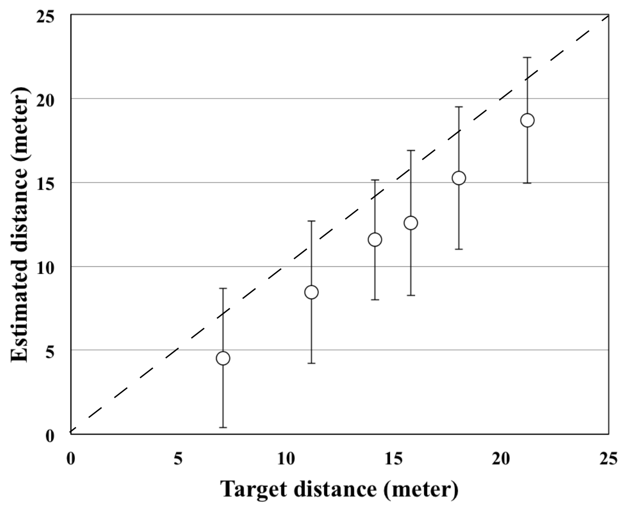


Figure 3.6: Results for the distance estimation task. The x-axis shows the actual target distances from the triangle completion task. The y-axis shows the pooled estimated distances of the participants. Due to symmetry, there were only six unique distances (lengths of hypotenuses). The error bars show the standard deviation. The diagonal dashed line illustrates the veridical matching.

As illustrated in Figure 3.5, participants significantly improved their performance to complete the task using the TriggerWalking technique over 4 sets of trials. After each round using a different condition, they required less time (approximately 4–6%) to complete the task without reducing their accuracy. The values for the average error for angle 30.4° (SE = 0.52) and distance estimation 4.0m (SE = 0.25) were the lowest in the last round.

A repeated measures GLM showed a significant decrease in the time required to complete the task. There was a significant effect for number of rounds on the required time $F(2.24, 51.40)$=38.10, p¡0.001 (using Greenhouse-Geisser correction) and a significant linear contrast between rounds $F(1, 23)$=31.05, $p < 0.001$. **These results support hypothesis H2.**

Figure 3.6 shows the results for the distance estimation task for all distances of the configuration described in Figure 5, ranging from 7.1m to 21.2m. A one-sample t-test showed that participants significantly underestimated the distance of all targets on average by 2.88m (SD=2.602) across all distances $(p < 0.001)$ and all conditions. **These results support hypothesis H1.**

Questionnaire

The results from the questionnaire suggest that condition F shows the highest value for the sense of presence, the highest value for the realism of walking sensation, and the lowest value for cybersickness. However, the within-subjects data were analyzed using repeated measures GLM with oscillation-type as the only factor (four levels) applied to the three questions displayed after each condition. This did not show significant differences between oscillation-types for the sense of being there (F(3,69) = 0.481, $p = 0.697$), cybersickness (F(3,69) = 1.522, $p = 0.216$) or realism (F(2.176, 50.06) = 0.725, $p = 0.5$) (using Greenhouse-Geisser correction). **Therefore, hypothesis H4 could not be confirmed.**

We found a mean SSQ-score of 84.8 (SD = 141.11) before the experiment and a mean SSQ-score of 307.22 (SD = 317.41) after the experiment. This difference was statistically significant as analyzed with a paired-samples t-Test (t(23) = 3.91, $p < 0.001$). The mean scores for the sense of presence (IPQ) were 3.8 (SD = 1.63) for general presence, 3.7 (SD = 1.03) for spatial presence, 3.1 (SD = 1.22) for involvement, and 2.7 (SD = 1.09) for experienced realism.

Each participant completed a NASA-TLX form after the experiment, to measure self-reported workload.

Participants ratings (Range (1-100)) were as follows:

- mental demand with a mean score of 44.3 (SD = 27.81)
- physical demand with a mean score of 37.2 (SD = 30.14)
- temporal demand with a mean score of 39.0 (SD = 26.18)
- performance with a mean score of 59.7 (SD = 24.18)
- effort with a mean score of 50.8 (SD = 27.31)
- frustration with a mean score of 36.8 (SD = 25.63)

3.3.6 Discussion

Overall, the results show that participants can use the bio-mechanically inspired TriggerWalking LUI to travel through a VE. Mental and temporal demands were evaluated as being quite high, whereas physical demand and frustration were evaluated as relatively low, showing that TriggerWalking itself was seen as incurring low fatigue. The analysis shows that users could quickly learn the technique. The results support previous findings of significant distance underestimation in VEs while using TriggerWalking. Participants evaluated the most realistic simulation of HMD oscillations (condition F) as most presence enhancing and most realistic, and also perceived the least amount of simulator sickness compared to all other conditions, but the differences were not statistically significant. Participants made significant errors during spatial judgments, which is also underlined by high scores for the self-reported mental and temporal demand on the spatial cognition task. To evaluate usability, we next compared TriggerWalking with Joystick, Teleportation, and Walking in Place techniques.

3.4 Confirmatory Study

We performed an experiment to compare the usability of four LUIs: TriggerWalking (TW), Walking in Place (WIP), Teleportation (T), and Joystick (JS) locomotion.

3.4.1 Experimental Environment

The experimental set up was similar to the setup described in Section 3.1.1. However, for this experiment, we used a complex VE of a realistic house with six rooms filled with objects (e.g., tables, beds, and benches). Coloured Easter egg targets were placed throughout the environment. We determined 48 possible locations, and the eggs appeared in 12 locations for each locomotion condition. To prevent users from hitting or trying to walk through walls or objects, we implemented collision detection in the VE. When a collision with a wall or object is detected, the display faded to black, indicating to the participant that they had collided with an object or wall and should move away from the object or wall.

3.4.2 Task

We placed 12 Easter eggs in the house and asked participants to find and procure all the eggs within three minutes. Each participant performed the task three times with different egg arrangements each time. Each egg

Easy Medium Hard

Figure 3.7: Screen-shots of the Easter eggs according to their difficulty

arrangement had six easy, four medium, and two hard egg placements as illustrated in Figure 3.7.

- **Easy**: Easter eggs were fully visible without any obstructions.
- **Medium**: Easter eggs were partially visible in corners or between tables, but careful observation was needed to find them.
- **Hard**: Easter eggs were placed below chairs or behind objects, and participants were told before the experiment to search the area thoroughly to find the eggs.

3.4.3 Procedure

All participants were given an information sheet outlining the experiment details and signed an informed consent form. Participants received further details on the four locomotion techniques being compared and completed a trial to familiarize themselves with the techniques. For the TW condition, two Vive controllers were used. Eggs were collected for TW, WIP, and T by intersecting the right controller with the egg. For WIP, two additional Vive tracking pucks[4] were attached just above the ankles of the subjects and subjects stepped in place to move using the same gait mapping as TW. For T, participants pressed the touchpad of the right controller to cast a ray on the ground to decide the next location to move to, and the user was teleported to the next location after releasing the touchpad. For JS navigation, participants used the left thumbstick of a wireless

Figure 3.8: Participant view during the experiment

Xbox controller, as shown in Figure 3.9 to control the speed of movement. The direction of movement is determined by the HMD view direction. When the participants moved near the Easter egg, it was highlighted to indicate that the participant was near enough. Then, the participant could collect the egg by pressing the 'A' button. The number of eggs collected was displayed on the rendered view. We used a time constraint of three minutes to pick up the 12 targets. The score is the number of eggs collected. We used locomotion technique as the independent variable, and the order of conditions was balanced using Latin square.

We chose our dependent variables to assess many of the characteristics of a good locomotion technique as they are presented in the literature [21, 172]. Table 3.2 shows the quality factors we studied and the measures we used to assess them. We employed the 1993 Simulator Sickness Questionnaire (SSQ) [71], the 1988 Standard Usability Scale (SUS) [25], and the 1988 NASA Task Load Index (NASA-TLX)[51]. These questionnaires are generally accepted *de facto* standard instruments for measuring respective phenomena. Each has a long history of use in the human factors community and more recently in VE evaluation studies.

[4]https://www.vive.com/eu/vive-tracker/

Figure 3.9: Xbox controller

Table 3.2: Quality factors and Measures

Locomotion Interface Quality Factor	**Measure**
Speed Control	Time
Positional Accuracy	Score and Collisions
Information Gathering (while moving)	Score (finding and collecting objects)
Easy to Learn	SUS Usability, Preference Questionnaire
Easy to Use	SUS Usability, Preference questionnaire
No Increase in Simulator Sickness	SSQ
Low Cognitive Load	NASA-TLX

3.4.4 Results

A total of 16 participants (five female, 11 male), aged 24-33 (M=26.9), completed the experiment. The collected data were analyzed with SPSS using a repeated-measures ANOVA with a Greenhouse-Geisser correction. The statistical significance level was set to $\alpha = 0.05$.

The mean and standard deviation values of Score, Time and Collisions for the four locomotion conditions are listed in the Table 3.3. There was no statistically significant difference between the scores ($F(2.759, 62.688) = 2.109, p = 0.112$) and time ($F(1.711, 25.658) = 2.242, p = 0.133$) for the four locomotion conditions. There was a significant difference in number of collisions between the four locomotion conditions ($F(1.762, 26.423) = 5.313, p = 0.014$). Post hoc tests using the Bonferroni correction revealed that JS had significantly fewer collisions than TW ($p = 0.002$) and T ($p = 0.004$).

Table 3.3: Mean and Standard Deviation of Score, Time, and Number of collisions

Measure	TW	JS	T	WIP
Score	M = 10.44 SD = 1.153	M = 10.50 SD = 0.966	M = 10.13 SD = 1.258	M= 9.56 SD = 1.548
Time	M = 167.76 SD = 25.69	M = 178.43 SD = 5.38	M = 173.53 SD = 17.29	M = 179.88 SD = 0.5
Collisions	M = 77.13 SD = 33.597	M = 49.00 SD = 21.34	M = 45.94 SD = 17.79	M = 65.38 SD = 54.079

We measured mean SSQ scores (higher scores means worse Cybersickness) of TW = 134.8 (SD = 179.21), JS = 333.8 (SD = 383.92), T = 139.1 (SD = 236.53), and WIP = 143.8 (SD = 168.45). We found that there was significant difference in SSQ scores of four locomotion conditions ($F(1.4, 21.01) = 5.572, p = 0.019$). Further post hoc tests using the Bonferroni correction revealed that JS induced more cybersickness than TW ($P = 0.049$) as shown in Figure 3.10.

The mean SUS scores were TW = 74.8, JS = 69.7, T = 76.1, and WIP = 69.8. There was no significant difference between SUS score for the four locomotion conditions ($F(2.669, 40.032) = 1.136, p = 0.342$). The mean and standard deviation scores of six sub-scales of NASA-TLX are shown in Table 3.4.

There was a significant difference in physical demand for the three locomotion conditions ($F(2.241, 33.6) = 10.33, p < 0.001$). Based on pairwise comparisons of these scores with Bonferroni correction, WIP had significantly higher physical demand than T ($p = 0.003$) and TW ($p = 0.003$) as shown in Figure 3.11.
The mean rankings (1 = worst, 4 = best) of the four techniques were TW = 3.2, T = 2.9, WIP = 2.3, and JS = 1.6. TW was the most preferred technique (nine out of 16 participants) followed by T, WIP, and JS. A paired-samples t-test showed a statistically significant difference between TW and JS ($t(15) = 3.755, p = 0.002$) and there was no significant difference in preference between TW, T, and WIP.

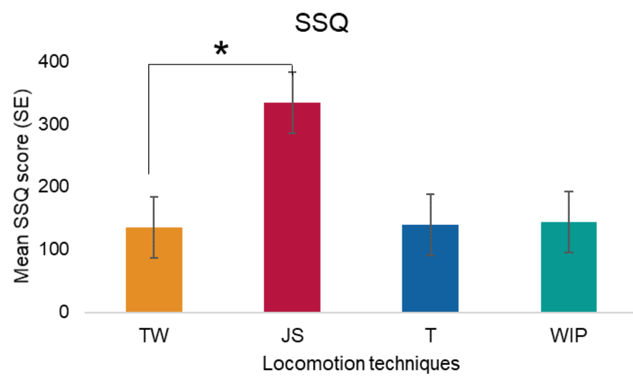


Figure 3.10: SSQ mean Scores with standard Error

SubScale	TW	JS	T	WIP
Mental Demand	M = 52.5 SD = 14.95	M = 54.7 SD = 16.24	M = 53.5 SD = 20.9	M = 62.2 SD = 17.82
Physical Demand	M = 40.4 SD = 18.13	M = 49.5 SD = 21.21	M = 37.0 SD = 20.72	M = 62.2 SD = 17.82
Temporal Demand	M = 51.6 SD = 19.65	M = 51.6 SD = 21.92	M = 46.9 SD = 18.80	M = 48.8 SD = 23.86
Performance	M = 68.2 SD = 23.92	M = 74.9 SD = 17.70	M = 73.5 SD = 19.85	M = 63.1 SD = 18.80
Effort	M = 48.5 SD = 15.75	M = 55.4 SD = 19.91	M = 47.8 SD = 17.35	M = 54.4 SD = 19.65
Frustration	M = 33.3 SD = 24.20	M = 44.0 SD = 30.25	M = 30.5 SD = 21.48	M = 37.6 SD = 24.33

Table 3.4: NASA-TLX scores (Higher Scores mean higher demand)

3.4.5 Summary of Confirmatory Study

We introduced TriggerWalking, which is a bio-mechanically-inspired LUI for efficient, we developed for realistic virtual walking in VR. TriggerWalking is a comfortable (low cybersickness and fatigue) LUI, which substitutes controller trigger pulls for the legs in actual walking and gives movement speed and direction control to the user. The technique is designed to make the locomotion experience less fatiguing and to avoid motion sickness.

Using the triggers of common VR controllers, the user can generate virtual bipedal steps. We analyzed head oscillations of VR users while they walked with an HMD, and used the resulting data to simulate virtual walking sensations. We evaluated how the simulation of walking bio-mechanics using our finger-based LUI affected task performance and spatial cognition. We did not find any significant influence of the different head oscillations on participant accuracy in spatial judgments. The results show that users can quickly learn the

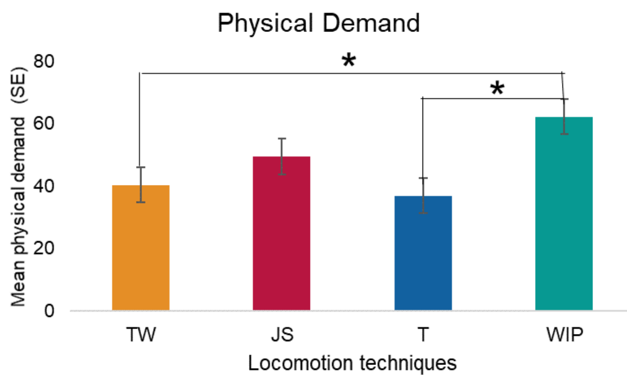


Figure 3.11: Mean physical demand scores with standard Error

TriggerWalking technique and significantly improve performance over time.

We also compared TriggerWalking with Teleportation, WIP, and Joystick locomotion techniques. Statistical analysis showed that TriggerWalking is less physically demanding than WIP, and induces less cybersickness compared to the Joystick. TriggerWalking and the other three locomotion techniques all use different kinds of input modes (Vive hand-held controllers, Joystick and foot trackers). Many consumer VR games and applications are controller-based, using different kinds of Joysticks or Game-pads, hence, in the next user study, we compared the usability of TriggerWalking to the game-controller based virtual locomotion techniques.

Virtual locomotion techniques almost always require that user interface devices and/or sensors (e.g., trackers) be part of the system. Using data received from the devices, locomotion techniques set both *speed* and *direction* of movement. For mass-market, the VE applications such as 3D games, implementing virtual locomotion using the affordance of user interface devices that are already part of the system, e.g., game controllers, not only saves money but builds on users' familiarity with the devices.

3.5 Comparing usability of game-controller based locomotion techniques

This section describes the user study we conducted to evaluate and compare three virtual locomotion techniques that employ interaction peripherals commonly used with or included in gaming and VE systems: joysticks, keyboards, and spatial controllers.

Relative low cost, simple operation, and availability of content development tools for consumer-grade Virtual Reality systems mean that they are increasingly adopted and used. A critical aspect of such systems is how easy it is for users to move in the VE. This movement, enabled by a virtual locomotion technique, is arguably an essential affordance of any VE system.

Study participants (N=15) performed a ”find and collect” task in a model of a furnished house, exercising their ability to use the different locomotion techniques to move through a crowded space similar to that in the confirmation study reported in the previous section. Using a counterbalanced, within-subjects, repeated measures design, we compared three locomotion techniques on efficacy (number of collectible objects collected, number of collisions, time to complete), simulator sickness, general usability, task load, and preferences.

The novel aspects of this work include:

- We implemented a locomotion technique using the *hip-worn* SpeedPad. While the keyboard (WASD) interface for locomotion is familiar to many, locating the SpeedPad on the hip is likely new to users, possibly negatively affecting their performance.
- Using qualitative and quantitative measures, we compared the usability of Xbox thumb-stick locomotion, SpeedPad locomotion, and the TriggerWalking locomotion technique described in the previous section.

Figure 3.12: Nostromo SpeedPad

3.5.1 System

This evaluation compared the usability of game-controlled based virtual locomotion techniques:

- **GamePad Locomotion using a thumb-stick (GP)**
  Participants controlled their speed of movement using the left thumb-stick of a Microsoft wireless Xbox

controller, as shown in Figure 3.9. Speed, rate of change in the user's viewpoint, was scaled linearly with the displacement of the thumb-stick from its centre rest position. Maximum speed, capped at 0.9 m/s, was achieved when the user pushed the thumb-stick to its maximum range in one direction. The direction of motion was the user's view direction as measured by the Lighthouse tracker and the HTC Vive HMD.

- **SpeedPad locomotion using keystrokes (SP)**
  The Belkin Nostromo SpeedPad n52 is a keyboard game controller peripheral, as shown in Figure 3.12. In our system, it was mounted on the user's left hip and operated with the left hand. The SpeedPad's keypad was used for locomotion in the VE, using typical first-person controls: 'Orange arrow up' to go forward, 'Orange arrow down' to go backward, 'Orange side arrows' for strafing left and right. These keys are physically arranged in the same pattern as WASD on a standard keyboard, which most desktop gaming applications use for movement. Tape with a rough surface was pasted on the keys used for locomotion to make sure that the users could identify the keys to use while they were wearing an HMD.
- **TriggerWalking using controller triggers**
  Trigger Walking (TW) uses the triggers of two Vive Handheld Controllers to mimic human bipedal walking. Each controller is analogous to a leg, and each trigger pull moves the user one step. The direction of movement is based on the average yaw orientation of the controllers. The speed can be increased by either increasing the trigger frequency (trigger-pull rate) or by changing stride length by changing the tilt angle of the controllers. Speed is scaled between .70 m/s and 2m/s for tilt angles between 0 degrees (arms and hands hanging down at rest) and 90 degrees (forearms and controllers at right angles to body).

The speed and direction settings of the locomotion techniques evaluated in this study are described in Table 3.5

Table 3.5: Speed and direction control for the locomotion techniques

Locomotion Technique	**Speed Control**	**Direction Control**
GP	Distance the stick is pushed from rest	HMD direction
SP	Constant speed based on key 'F' press	HMD direction
TW	*Step frequency* by increasing the frequency of triggering the Vive controller. *Step length* by the angle of controllers relative to the floor.	Average of the yaw angles of the two controllers relative to the Unity Game Camera axis

3.5.2 Methodology

To analyze the usability, simulator sickness and physical demand of the three locomotion techniques, we conducted a within-subject, repeated measures user study with locomotion technique as an independent variable with three levels: GamePad (GP), SpeedPad (SP), and TriggerWalking (TW).

Participants

This experiment was approved by the University of Canterbury Human Ethics Committee. All participants read and signed a consent form. There were 15 participants, including eight male and seven female, with an average age of 30. All participants had normal (5) or corrected to normal eyesight (10). All participants but one were right-handed. Eight participants had good knowledge of 3D games; seven participants play 3D computer games every week.

Equipment

The study was conducted in a 7m$\times$5m room. We used an HTC Vive HMD, which provided a resolution of 1080 x 1200 pixels per eye. The diagonal field of view was 110° with a refresh rate of 90 HZ. The pose (position and orientation) of the HMD in all conditions and the pose of the Vive controllers in the TW condition were tracked using the Lighthouse tracking system. For the GP condition, we used the left thumb-stick on the Microsoft wireless Xbox controller. We used the Belkin Nostromo SpeedPad n52 for the SP condition. The computer used in the study was an Intel Core i7-6700 processor, with 16GB of main memory, and an NVIDIA GeForce GTX 1080 graphics card.

Virtual Environment

This experiment used the same VE used in the confirmation study, as described in the previous section. It was a realistic model and rendering of the interior of a house that had six rooms and a corridor connecting the rooms. A screenshot of the room is shown in Figure 3.13. Navigation in the house was somewhat difficult, due to the presence of tables, chairs, beds, cabinets, indoor plants, and other furnishings.

Each participant performed the task three times with a different egg arrangement for each locomotion condition. This task was repeated for the other two locomotion conditions. Since each participant completed the task three times, to mitigate any effect of the order of conditions, the order of conditions was counterbalanced across participants. Each egg arrangement had six easy-, four medium-, and two hard-to-find eggs, as illustrated in Figure 3.7. In the GP condition, participants moved using the left thumb-stick. Eggs were collected by moving towards the egg and pressing the 'A' button on the Xbox controller. In the SP condition, participants used 'WASD' to move around the environment. Eggs were collected by moving towards the egg and pressing the left alt button. In the TW condition, participants navigated in the environment using the triggers of the Vive controllers. To pick-up the eggs, they had to touch the egg with the right controller. In the experiment, we

Figure 3.13: Participant view of a room in the VE

hypothesized that TW would be rated as more usable, more preferable, and inducing less simulator sickness and fatigue than the JS, WIP, and T conditions.

Measures

We collected demographic information with a questionnaire before the experiment. In addition to gender and age, this included information about knowledge of and frequency of playing 3D games. Participants completed the Simulator Sickness Questionnaire (SSQ) to provide a baseline value for use in later analyses. Time to complete the task was measured. The number of eggs collected, the *score*, was counted to compare the efficacy of the techniques, i.e., how well users could find and collect the eggs.

We administered three standard questionnaires after each trial run to evaluate and compare our techniques on the interface quality factors, as shown in Table 1. The questionnaires were:

- *Simulator Sickness* was measured using the Kennedy-Lane SSQ before the experiment and after each task condition.

- *Usability* of the techniques was measured using the Standard Usability Scale (SUS) questionnaire. SUS is a ten-item questionnaire with responses on a 5 point Likert scale. (Note, this is not the Slater, Usoh, Steed Presence questionnaire.)
- *Task Load Index* was measured using the NASA Task Load Index (NASA-TLX). The NASA-TLX measures Mental demand, Physical demand, Temporal Demand, Performance, Effort, and Frustration.

In addition to the questionnaires, after completing the three trials, participants rated their preference for each of the three locomotion techniques on an 11-point scale and explained factors influencing their high and low scores.

Experimental Session

Participants were introduced to the equipment used in the experiment and were informed in detail about the tasks and conditions. Then, they had a short training session on each locomotion technique. When the participants indicated they were ready, the experiment environment was loaded, and the participants were instructed to find and pick up the eggs within three minutes.

3.5.3 Results

The statistical analyses were performed using SPSS 24 for Windows. For ordinal data, related-sample non-parametric tests were used. For other data, repeated-measures ANOVA with a Greenhouse-Geisser correction was used. Pairwise comparisons were corrected using Bonferroni corrections when appropriate. Significance level was set to 0.05.

Performance Metrics

To evaluate the difference in performance for different techniques, we measured score, time, and collisions. As shown in Table 3.6, the mean score for TW was highest followed by SP and GP, respectively. Since there was a restriction on time, the mean time taken (in seconds) to pick up the eggs was nearly three minutes (180 seconds), we saw a trend of GP having slightly lower time taken than TW as seen in Table 3.6. The collisions while using TW were higher than GP and SP conditions.

Table 3.6: Mean and SE of Score, Time, and Number of collisions

Measure	GP	SP	TW
Score	M = 9.2 SD = 0.38	M = 9.4 SD = 0.56	M = 10.27 SD = 0.40
Time	M = 180.0 SD = 0.00	M = 173.3 SD = 3.94	M = 175.5 SD = 2.60
Collisions	M = 50.6 SD = 3.90	M = 46.6 SD = 4.92	M = 68.8 SD = 7.44

There was no statistically significant difference between scores (F(1.951, 27.318) = 2.646, $p = 0.09$), and time taken to complete the tasks (F(1.673, 23.421) = 1.976, $p = 0.166$) in the three locomotion conditions. The difference between number of collisions was significant (F(1.37, 19.182) = 5.823, $p = 0.018$). Post hoc tests revealed that there was significant difference in collisions between SP and TW $(p = 0.034)$. There was no significant difference between GP and SP $(p > 0.99)$ or GP and TW $(p = 0.141)$.

Questionnaires

Table 3.7 shows the mean and standard deviation values of SSQ scores (incr.), SUS scores, and NASA TLX. From Table 3.7 and Figure 3.14, we observed a trend showing TW having lower SSQ scores than GP and

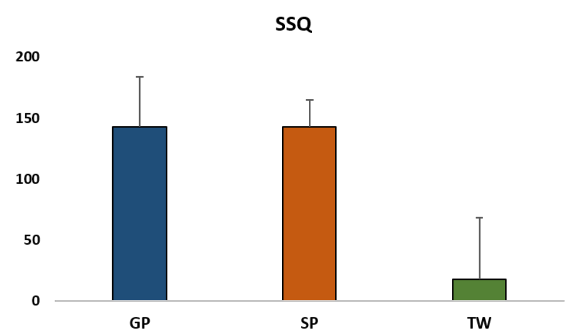


Figure 3.14: SSQ Scores

SP. There was a statistically significant difference between SSQ scores of GP, SP, and TW (F(1.593, 22.301) = 6.343, $p = 0.005$). Post hoc tests revealed that the SSQ score of TW was significantly lower than GP $(p = 0.009)$. There was no significant difference between SSQ scores for GP and SP $(p > 0.99)$ or SP and TW $(p = 0.74)$.

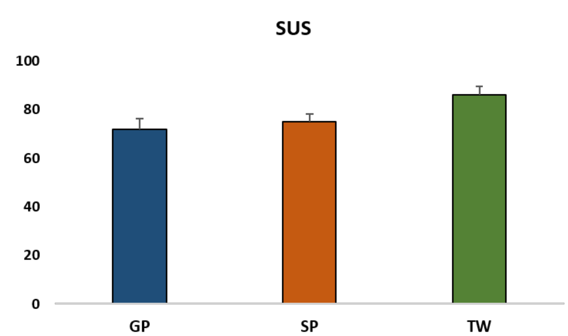


Figure 3.15: SUS Scores

We found a statistically significant difference between SUS scores of GP, SP, and TW (F(1.909, 26.723) = 4.768, $p = 0.017$) as seen in Figure 3.15. Post hoc tests revealed that there was a significant difference between GP and TW $(p = 0.041)$. There was no significant difference in SUS between GP and SP $(p > 0.99)$or SP and TW $(p = 0.065)$. Figure 3.16 shows the NASA-TLX scores for the three locomotion techniques. We found no significant difference between NASA-TLX scores of GP, SP, and TW (F(1.397, 19.561) = 1.505, $p = 0.097$).

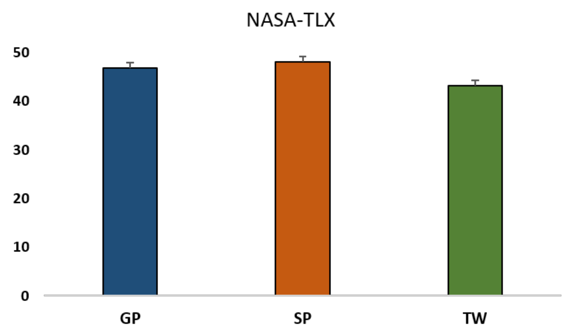


Figure 3.16: NASA-TLX Scores

Participants had a significant difference in preference between GP, SP, and TW (F(1.857, 24.147) = 12.1, $(p < 0.001)$. TW was the preferred choice compared to GP $(p = 0.006)$ and SP $(p = 0.003)$, respectively. The preference scores between GP and SP were not significant $(p > 0.99)$.

Table 3.7: Mean and Standard Deviattion of SSQ, SUS, and NASA TLX

Measure	GP	SP	TW
SSQ (incr.)	M = 142.65 SD = 41.13	M = 142.76 SD = 50.5	M = 17.56 SD = 21.8
SUS	M = 72 SD = 4.38	M = 75.17 SD = 3.37	M = 86.17 SD = 3.03
NASA TLX	M = 46.89 SD = 3.93	M = 48.16 SD = 3.86	M = 43.23 SD = 4.66

A thematic analysis was performed on the written comments provided by the participants at the end of the study. The analysis showed that the main problem associated with GP use was that it increased symptoms of simulator sickness (four mentions) and disorientation (two mentions). One participant also named simulator sickness as the negative experience with the use of SP. Lower performance associated with the use of GP was mentioned twice. Concerns with the ease of use and unfamiliarity with the interface were additional criticisms of SP and were mentioned five times. The use of TW was criticized once as too inconvenient because it required more body movement than the other two interfaces. However, TW was rated positively by participants because of the lower simulator sickness (three mentions), its support for better performance (four mentions) and the highest ease of use and naturalness of the user interfaces (11 mentions).

3.5.4 Discussion

Overall, the mean number of eggs collected in all conditions was similar across the conditions. Since each environment had six easy and four medium eggs, most of the participants had a score value of 10. However, to pick up the last two (hard) eggs, participants needed good ability to move through VE quickly and simultaneously observe the environment to find the partially obscured eggs. This need for careful observation may be one of the reasons for the mean value of Score being around 10. A time cap of three minutes for completing the task made the task more challenging and engaging. The mean time taken over all the conditions was three minutes, showing a ceiling effect. The number of collisions in the VE while using TW was significantly higher when compared to the GP and SP conditions. The ability to move much faster by increasing the trigger frequency could be one of the reasons for the higher number of collisions. There was little ability to change speed (increase/decrease) with the GP and SP techniques.

While we did not measure other quality factors such as spatial awareness and orientation, presence, and immersion directly, the open-ended participant comments addressed some of them. For example, comments on disorientation apply to the quality factor ”spatial awareness and orientation.” Three factors related to equipment can be directly observed. Locomotion techniques should require minimal additional infrastructure (none in TW case), minimal encumbrances when worn or carried by the user (no additional devices in our case), and hands-free operation (only half correct for our techniques). The ability to elicit the illusion of presence is a very important quality factor for VE systems. As our focus was on locomotion, we did not measure presence.

Participants using artificial locomotion techniques such as GP and SP experienced significantly high simulator sickness compared to TW. The results support previous findings. The Simulator sickness and disorientation scores were significantly worse for GP and SP, and that could be the reason for their low preference levels. The SUS scores of the different conditions suggest that TW is more usable for locomotion compared to GP and SP. Participants perceived ability to control movement using the controllers as easy and realistic, however, one participant criticized it as being inconvenient.

In conclusion, we compared and evaluated the usability of three controller-based locomotion techniques to navigate in VEs. The aim of this study is not to compare the form factor of the hardware used. It is to compare the internal working of TriggerWalking compared to the GamePad and SpeedPad. We implemented and compared locomotion techniques for an Xbox GamePad, a Belkin Nostromo SpeedPad gaming keyboard, and HTC Vive hand controllers. From the results, we found that the performance with the GamePad and SpeedPad were similar and that both were fairly accurate. Overall, however, TriggerWalking showed better efficacy and was the participants' preference. Furthermore, TriggerWalking induced less simulator sickness compared to the GamePad and SpeedPad.

3.6 Summary

In this chapter, we described and evaluated our novel bio-mechanically inspired locomotion technique, TriggerWalking. In the evaluation, TriggerWalking had better usability and comfort compared to other commonly used Teleportation and Joystick locomotion techniques. However, TriggerWalking is mostly suitable for small-scale or medium-scale environments. It is not suitable for large-scale environments since it might induce finger fatigue after prolonged use due to trigger press for each step, and might be considered inefficient for long-distance travel by the user. Since TriggerWalking uses both the controllers, it is also not suitable for tasks that involve the need for interaction using controllers.

No single locomotion technique is suitable for all VEs and tasks. There is a need for a framework that helps game developers choose suitable locomotion techniques depending on the environment's size and the task. The next chapter explores the attributes of such a framework and proposes a testbed to evaluate such a locomotion technique framework.

Chapter 4

LUTE: A Testbed for Locomotion Studies

The previous chapter discussed the implementation and evaluation of TriggerWalking(TW) and compared it to Teleportation (T), Walking-in-Place (WIP), Joystick (JS) and SpeedPad (SP). The analysis showed that TW was a comfortable and efficient locomotion technique for short-medium distance travel. TriggerWalking is not ideal for long-distance travel or travel tasks that require both hand-held controllers for other tasks (For example, if the additional task is to shoot at objects while moving, we cannot use the two hand-held controllers). To perform locomotion tasks in a complex VE, a single locomotion technique might not be enough. In this chapter, we introduce the concept of *Multi-Travel mode(M-Travel mode)* that has a suite of locomotion techniques to travel in a complex VE and accomplish several travel tasks. To evaluate the Multi-Travel mode and compare it to other existing locomotion techniques, we developed a standard testbed environment which accommodates short-, medium-, and long-distance travel. We developed a Locomotion Usability Test Environment (LUTE) to enable the systematic evaluation of locomotion techniques.

4.1 Introduction

According to Bowman et al. [22], using formal testbeds in evaluating interaction techniques not only leads to a greater understanding of the techniques but also helps in developing robust and better techniques using the knowledge gained through evaluation. Bowman et al. [19] define *testbed* as an environment in which many objects of the same type can be evaluated, even if they had not yet been proposed or created when the testbed is developed. Lampton et al. [85] used a Virtual Performance Assessment Battery (VEPAB) to evaluate interaction techniques, including locomotion techniques. VEPAB consisted of different building interiors to evaluate tasks of five categories: vision, locomotion, tracking, object manipulation, and reaction time. Bowman et al. [20] used a testbed evaluation framework (an open medium-sized environment with obstacles) to evaluate the performance of different locomotion techniques in search tasks. Nabiyouni and Bowman used a formal testbed (an indoor hallway with turns) to evaluate hyper-natural transfer function of locomotion techniques [102]. Albert and Sung developed a VRL testbed with each area targeted for a particular task. For example, the testbed had an outdoor park scene aimed to reduce the sickness by focusing on a stationary object and a treasure search in a maze task to evaluate spatial awareness.

To find locomotion technique best suitable for each environment size and task, we need a testbed that can accommodate VE's of different sizes and tasks. Hence, we developed LUTE, a Locomotion Usability Test Environment to evaluate the locomotion techniques for different environment sizes and tasks. In order to design LUTE, we came up with different attributes that can be included in testbed by evaluating the travel task, VE, and VR system. In this chapter, we discuss the factors affecting appropriate selection of attributes needed for a testbed to evaluate locomotion techniques best suitable for the travel task, VE, and VR system. Finally, we discuss our implementation of LUTE and the attributes we considered as essential.

Chapter Roadmap

This chapter has the following sections:

- *Initial Evaluation of the travel task, VE, and VR system*
  In this section, we will discuss different factors affecting the selection of suitable locomotion techniques based on the VE and the tasks.

- *LUTE: Locomotion Usability Testing Environment*
  In this section, we discuss desirable attributes of a locomotion testbed. Further, we discuss the implementation of LUTE and its attributes.

4.2 Factors for appropriate locomotion selection

To be able to design a locomotion testbed, we need to understand the different factors that affect the suitability of a locomotion technique to a particular travel task. First we focus on understanding the task and the VE in the VR application. Considering human factors issues that affect user performance, for example, the physical and mental effort depends on the task in VR. Understanding the task and its requirements is a first step to select a locomotion technique from among existing techniques based on the requirements of the VR application.

4.2.1 VR System Characteristics

It is important to take into account system characteristics such as tracking space, input devices, user posture, UI, and additional sensors when choosing a locomotion technique. Natural locomotion techniques such as

Real Walking and Redirected Walking need a room-scale tracking area. A VR device such as HTC Vive is suitable for natural locomotion techniques, but VR devices that allow only standing/sitting such as Playstation VR cannot be used for VR application that needs room-scale tracking. The hand-held controller setup also plays a vital role in choosing a suitable locomotion technique. If the locomotion technique requires 6DOF rotation and if the controller is not tracked, then it is not suitable for our needs.

4.2.2 Task Characteristics

In most of the VR applications locomotion is not the primary task. Locomotion enables the user to accomplish the primary task, e.g., collect objects. According to Bowman et al., we have to consider different travel characteristics related to task while selecting/designing locomotion techniques [22]:

- **User's goal for the Travel task**: Bowman et al. classify the primary user's goal for the travel task as exploration, search, and maneuvering [22]. In the exploration task, the user is browsing an environment, and there is no explicit goal. In the search task, the user's goal is to travel to a precise target location. In the maneuvering task, the user's goal is to move precisely. For example, moving precisely to avoid colliding with objects in a narrow path.
- **Scene Complexity**: Scene complexity includes the number of bends, turns, the width of the path, static, and dynamic obstacles/distractors, and visibility (vegetation in the VE).
- **Number of DOF required for the movement**: In cases where the travel task requires motion in a horizontal 2D plane, the locomotion technique should not force the user to travel in other dimensions.
- **Required accuracy of movement**: Travel tasks such as travelling through a narrow maze without colliding with walls require a locomotion technique to help the user control the accuracy of the movement.
- **Required speed of the movement**: Some tasks demand the user to reach a target quickly.
- **Other primary/secondary tasks**: In most of the VR applications, locomotion is a secondary task. The primary task or additional tasks affect the cognitive load of the user. If the cognitive load for the primary task is high, locomotion technique selected must have a lower cognitive load to ensure better performance of the user. For example, consider an example scenario in which the task is to draw and release an arrow using both the hand-held controllers. The primary task is to shoot arrows at the target, and if we include a locomotion technique that uses hand-held controllers, it would be overwhelming for the user to complete both the tasks.

4.2.3 Environment Characteristics

Attributes of the VE play a significant role in selecting an appropriate locomotion technique. Different environment sizes have different locomotion requirements. For example, if the scale of the environment is large (travel to another city), it is not ideal to use Walking-in-Place or Redirected Walking. Locomotion techniques that use walking metaphors are suitable in VE which are medium to small. Scene complexity is another factor

Asset Attributes	Subdivision	Description
Environment Size		Environment size can be selected for long-, medium-, and short-distance travel.
Path Complexity	Number of turns and bends	More turns and bends in the path increases the complexity of the path.
	Road width	Road width helps in defining the required precision of the locomotion task. The number of collisions with objects beside the road (trees or bushes) typically increases with a decrease in the width of the road.
	Road textures	road textures can be manipulated to study presence, for example. The texture gradient in the real world has been found to increase the accuracy of distance estimation.
	Obstacles	Obstacles can be static, such as grass, shrubs, trees, stones or other objects on the road, or dynamic, such as animals, humans, vehicles, etc.
	Dynamic Weather	Weather simulation in video games has been shown to increase realism in the game [139]. Extreme weather conditions, e.g., fog and rain, affects the visibility of the environment.
Indoor Environment	Elevations and steps	The complexity of the tasks in indoor environments can be increased by including elevations and steps.
	Complexity	The complexity can also be increased by adding turns, bends, and obstacles in indoor environment/
Landmarks		Pierce and Pausch [119] showed that visible landmarks led to faster locating of destinations.

Table 4.1: LUTE Asset attributes (The attributes shaded in grey are implemented in LUTE)

that affects the selection of locomotion technique. Previous research [24] has shown that some locomotion techniques such as Teleportation perform well in VEs which have less complexity and high visibility (clear line of sight) compared to a complex environment. Hence, factors such as distance to be travelled, and the complexity of VE are essential factors in choosing a suitable locomotion technique for a specific task in VR.

Based on the factors discussed, a locomotion testbed should minimally have the flexibility to manipulate the attributes listed in Table 4.1 based on the travel tasks.

4.3 LUTE: Locomotion Usability Testing Environment

In this section, we discuss a practical implementation of the Locomotion Usability Testing Environment (LUTE) to evaluate the comfort and usability of locomotion techniques in VE. The current version of LUTE has been realized using the Unity3D game engine. LUTE gives the researcher choices in terms of path length

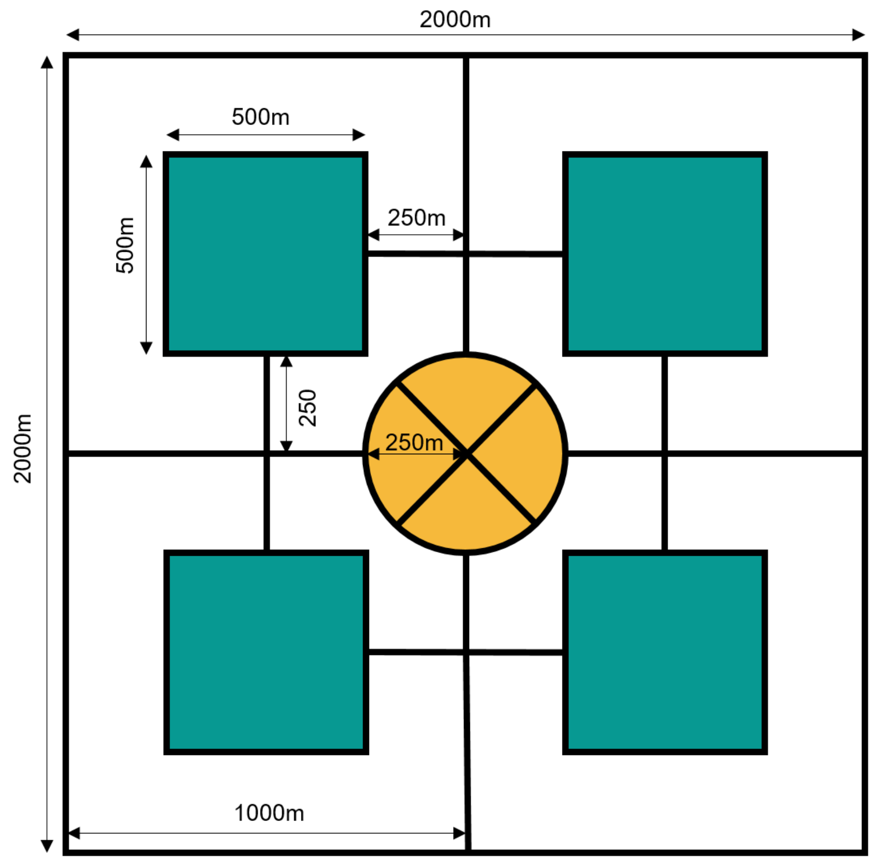


Figure 4.1: Blueprint of test environment

and complexity (vegetation, road width, bends, and turns). Based on these choices, LUTE generates possible paths which have equal lengths, turns, and bends. For example, if the researcher chooses to have a path with a length of 5000 metres and two turns, eight paths will be generated, and the researcher can choose to use one path or up to eight paths. If the researcher wants to compare different locomotion techniques, the path parameters can be held constant to avoid bias. Currently, LUTE includes two examples of indoor environments: an open space, as shown in Figure 4.2 and a maze[1] as shown in Figure 4.3. If researcher needs to have a particular indoor environment, it is easy to add the Unity prefabs in LUTE environment.

We created a system to autogenerate paths for participants to navigate based on selections made by the researcher . Figure 4.4 shows the LUTE attribute selection interface. The interface allows researchers to select the environment type. If the environment chosen is large or medium, the predefined path lengths can be selected. If the environment selected is small, then the scene with a small-scale space will be uploaded. The

[1]https://assetstore.unity.com/packages/3d/environments/historic/egyptian-labyrinth-84280

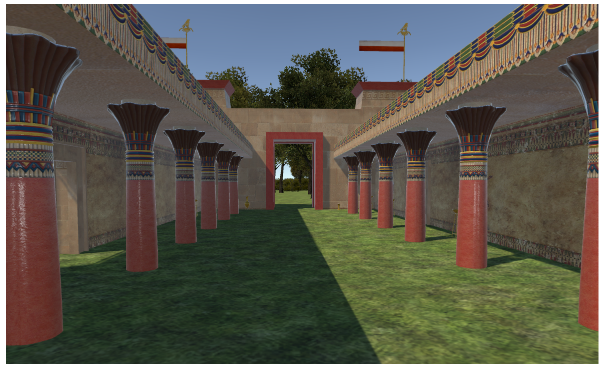


Figure 4.2: Indoor Environment

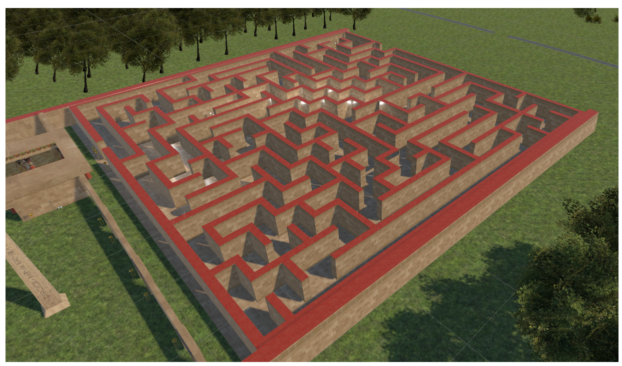


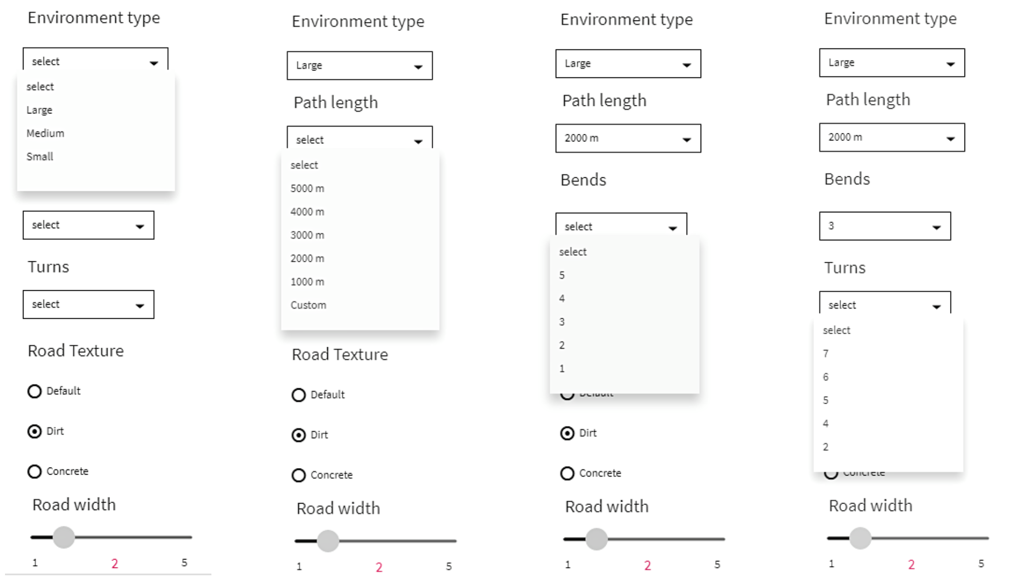
Figure 4.3: The maze currently avaiable in LUTE

path length, bends, and turns can be selected by the researcher. The choice of the number of bends and turns available depends on the path length (i.e., if the path length is longer, the path can accommodate more bends and turns).

Figure 4.1 represents the blueprint of the test environment with standardized road-section lengths. The roundabout in the middle can be used to increase the complexity of paths by adding curved roads and bends. The green areas are shown in Figure 4.1 can be populated with structures, such as buildings or mazes, that require shorter distance locomotion. Thus, LUTE can support higher-level locomotion tasks that require, for example, a user to navigate from one area to another (long-distance travel), then enter a building to find a particular room (medium-distance travel), and finally pick up an object from a desk.

4.3.1 Asset attributes in LUTE

Table 4.1 describes the different test environment attributes. The ones currently implemented in LUTE are discussed in more detail below.



Environment size　　Path length　　Bends　　Road texture and Width

Figure 4.4: Asset attribute selection user interface

Environment Size

In LUTE, based on the requirement of the evaluation, we can select the size of the environments.

Path Lengths

Path lengths can be manipulated based on the requirements of the locomotion task and goal of the user. For example, to evaluate the speed of a locomotion technique, long paths can be used.

Path Complexity

Zhai and Woltjer [184] conducted a user study on human movement performance about path constraints and found that participants' mean trial completion times for the tasks were linearly correlated with an index of difficulty. Their index of difficulty was quantified as the path length to width ratio for straight and circular paths. Some of the desirable attributes of locomotion techniques are precision and speed. Road width helps in defining the required precision of a locomotion task. The number of collisions with objects beside the road (trees or bushes) increases with a decrease in the width of the road. The width of the road also affects the index of difficulty, which, in turn, affects the task completion time.

In the Zhai and Woltjer[184] study, the path width affected the attention behaviour of the participants. Participants' subjective indications revealed that they looked farther ahead while moving on wide roads and looked closer in on narrow roads. This behaviour may have affected their efficiency in doing the task; however, analyzing reliable eye-tracking data could further reveal and validate this assumption. Both of these attributes can be compared by taking paths of different complexity. The index of complexity is yet to be standardized. In LUTE, we allow path complexity to be increased or decreased by varying road width, the number of turns, and obstacles. Static or dynamic obstacles can be added to LUTE to increase the complexity.

Obstacles

Visibility plays a role in contemplating the path taken by the user [184]. If the path is visible, users can estimate the speed and precision needed to travel and choose the suitable locomotion technique to reach their desired destination efficiently.

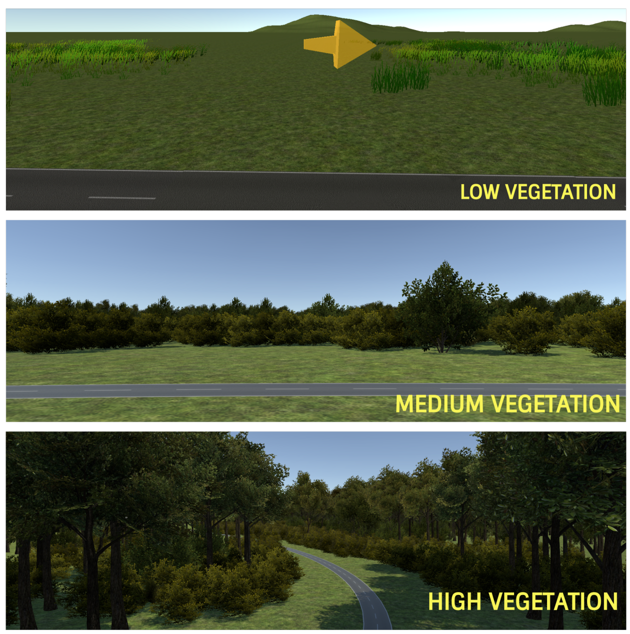


Figure 4.5: Different levels of Vegetation. From top; low (with an arrow to guide users along the path), medium, and high vegetation

If the path is partially obscured, the user has to think more about how to avoid taking the wrong path or colliding with objects. Visual attention tendencies while using different locomotion techniques can be studied if the visibility of the road is varied. LUTE supports three levels of vegetation: The low-vegetation terrain (top Figure 4.5) has only grass texture that is physically short, and the visibility is high. The medium-vegetation terrain (middle Figure 4.5) has some shrubs and bushes that slightly obscure the path if it is not straight. The high-vegetation terrain (bottom Figure 4.5) has trees and the visibility, especially at the bends, is very much lower.

Indoor Environment

In LUTE, we included an indoor environment (a Unity prefab) to allow us to evaluate a locomotion technique for small-medium distance travel. Additional prefabs can be dropped in the Unity environment in the green rectangular or yellow sector areas, as seen in the blueprint in Figure 4.1.

Figure 4.6: Tower as a landmark at the centre of the environment

Landmarks

Landmarks help as anchors to give the user a sense of direction. A tall tower, as shown in Figure 4.6 was placed in the centre of the environment to assist the users if they get lost in the vegetation.

4.3.2 Contribution of LUTE to Research Community

In current studies on locomotion, it is hard to compare the results of different studies since each study use different VE and tasks. There is no common test bed based on which multi-level or multi-scale locomotion techniques can be evaluated. LUTE is a tool designed to help researchers evaluate different locomotion techniques. In LUTE, the researchers has the ability to change the asset attributes like VE size and complexity so that if another researcher needs to compare a new locomotion technique, the same set of conditions can be used to have the same base setup.

4.4 Summary

In order to evaluate locomotion techniques in a complex VE, we developed a locomotion usability test environment (LUTE). LUTE has many practical implications. Firstly, this approach into evaluation suggests a systematic and formal view of locomotion techniques which can guide developers in identifying the drawbacks of a certain technique. Secondly, researchers can compare the locomotion techniques with existing studies with minimal work. Thirdly, using LUTE, developers can systematically optimize the design of existing techniques to achieve the best usability by finding the limitations of the techniques by systematic evaluation. Fourthly, the optimization of locomotion techniques is a first step to identifying the gaps in the locomotion literature and working towards developing new and exciting locomotion techniques in the future. The next chapters explain two user studies to evaluate Multi-Travel mode using LUTE.

Chapter 5

Multi-Travel Mode (Pre-selected)

The previous chapter discusses the need for a systematic evaluation of locomotion techniques and describes the implementation of a testbed asset LUTE. LUTE is designed to help us evaluate locomotion techniques in the complex VEs with spaces of different sizes and task scenarios. In this chapter, we introduce Multi-Travel mode (M-Travel mode) with pre-selected locomotion technique, and discuss user study conducted to evaluate it.

5.1 Introduction

Most locomotion techniques provide partial solutions and are suitable for particular scenarios. For example, to travel a long distance, it would be preferable to use vehicular techniques or a non-natural technique such as Teleportation rather than walking. If the environment is room-scale and if the task in the game demands the player acquire spatial knowledge of the environment, then walking would be suitable. If the task in VE is to travel and shoot an arrow using two hand-held controllers, then techniques that use the controllers, such as TriggerWalking or Joystick, are not ideal since the controllers are used for navigation. Other considerations include available physical space, fatigue, precision, physical requirements for a task, and additional hardware needed. An ideal locomotion technique is also expected to optimize factors such as comfort (e.g., lack of cybersickness), speed, accuracy, presence, and learnability [82]. Currently, no single locomotion technique in the literature (refer to background section for details) can deliver all of those desirable attributes for all VR application scenarios. One approach is to consider the problem of locomotion in VR as we approach to travel in the real world: i.e., people use different modes of transportation and locomotion when they are travelling different distances and performing different tasks based on travel distance, task requirements and preferences.

M-Travel mode offers different pre-selected locomotion techniques for different travel distances. The M-Travel mode uses Teleportation for long-distance travel, Thumb-pad locomotion for medium-distance travel, and TriggerWalking for short-distance travel. Often, virtual environments are explored standing up, which is one of the contributing factors of physical fatigue since it involves high energy expenditure compared to sitting. To evaluate the M-Travel mode and pose (sitting and standing), we used LUTE. We tested the user performance, usability, and comfort of the between-subjects effect of travel technique (M-Travel mode, Teleportation or Thumb-pad locomotion in isolation) and within-subject effect of pose (seated/standing). While M-Travel mode did not outperform the other two locomotion techniques, we found that participants prefer Thumb-pad locomotion while sitting and prefer Teleportation while standing. Cybersickness was significantly higher while using Thumb-pad locomotion compared to Teleportation.

This chapter describes the evaluation carried out to understand the requirements for suitable locomotion techniques based on the travel tasks, the posture of the user, and the VE. Further, we discuss the rationale behind choosing the task and the locomotion techniques included in M-Travel mode with pre-selected locomotion choice, and a user study to compare the user performance of M-Travel mode to Tele and TPad. In the end, we analyze and discuss the results.

5.2 M-Travel Systems in the literature

Bhandari et al. [9] developed *Legomotion*, a scalable walking travel technique that enables users to seamlessly switch between Walking and Walking in Place for virtually navigating in a VE that is larger than the physically confined and limited tracked area. When compared to joystick control, they found that using *Legomotion* increased the sense of presence. However, several participants preferred the joystick over *Legomotion* since they were more familiar with it. Sanders et al. [179] presented a system to explore a large VE by scaling the step length and by increasing the eye height. The results showed that the scaling gain non-linearly is an effective method of exploring a large VEs. However, they found that scaling the eye height does not result in better spatial orientation that scaling gain using the participant's normal eye height.

Arnskov et al. [5] developed a travel framework *Locomotion*^{3}, that allowed users to freely alternate among real walking, walking in place (WIP), and a skateboard metaphor to accommodate both precision and efficiency. The Arnskov study compared the performance of participants who used *Locomotion*^{3} to participants using only one of WIP or the Skateboard metaphor. The analysis showed that having an increasing number of obstacles in the environment increased task completion time regardless of the travel technique used. However, no information was presented in the paper on participant behavior while switching between the techniques.

Cmentowski et al. [35] developed a multi-perspective, or multi-viewpoint, travel approach called *Outstanding*. This technique allows users, on-demand, to switch from a first-person view of the environment to a third-person bird's eye view. The method used arc-based teleportation in both perspectives to allow users to efficiently navigate shorter (first-person view) and longer (bird's eye view) distances. The study found that compared to conventional teleportation, having the choice to switch between perspectives on demand increased participants' spatial orientation and decreased instances of cybersickness. They also found that participants were able to switch between techniques intuitively without any confusion.

Salvetti et al. [127] developed a locomotion system to smoothly transition between two walking metaphors: Real Walking and Walking in Place. Their pilot study had users walk around a large virtual train station environment. Their results showed that users exhibited low cybersickness and high immersion.

In previously reported studies of systems allowing multiple modes of travel, researchers did not investigate, or report whether, at any particular time and place in the VE exposure, the participants chose one technique over another due to characteristics of their task or of the VE itself. As suggested by the Legomotion paper, another factor affecting travel technique choice may be prior experience and familiarity. Ruddle et al. [133] investigated the effect of training time on the proficiency of participants who used a joystick, HMD-directed, and Omnidirectional treadmills. Based on the results of that study, Ruddle recommended training participants to a proficiency criterion rather than for a fixed length of time. We follow this recommendation in our work to minimize the effect of familiarity on the choice of travel technique.

5.3 Initial Evaluation

5.3.1 Tasks

We chose the following tasks to evaluate M-Travel mode:

1. Travel along a road or path with good clearance and good visibility similar to the study done by Kitson et al. [77]: Specifically, our long-distance task was to follow course indicators along a road with minimal obscuring vegetation and objects.
2. Explore space and, find and collect objects similar to the study done by Peck et al. [117]
3. Maneuver through a crowded space and avoid colliding with objects in the space similar to the study done by Langbehn et al. [87].

5.3.2 Pose

In several user studies that evaluated locomotion techniques in VR, users were standing while performing the tasks [157, 102, 104, 134, 135]. This indicates that energy expenditure while standing is more than sitting. Noah et al. [36] studied the performance of joystick navigation while sitting and standing, and found no difference in the performance. Terziman et al. [160] evaluated WIP while sitting and standing and found that realism is higher while sitting than standing. However, Carello et al. [31] found that users overestimate target distance while standing and underestimate target distance while sitting. Sitting is a natural (computer games, eating, driving, using a computer, riding in a car, etc.) pose that is more comfortable than standing. In addition to evaluating the locomotion techniques for different tasks, we also evaluated the locomotion techniques for different poses (standing and sitting). An additional requirement was that users not be required to change their interaction device should they choose to change the locomotion technique during a virtual experience.

5.3.3 Locomotion Method Selection

The initial evaluation helped us understand the requirements for suitable locomotion techniques that could be used. We chose locomotion techniques that were well suited for long-, medium-, and short-distance travel. We eliminated from consideration any technique that was known from previous research to cause elevated levels of cybersickness in users, e.g., joystick flying, and for long-distance travel, any technique that induces fatigue when used over time, e.g., natural walking. For short travel distances, the technique had to offer easy speed and direction control for close-quarters maneuvering. Thumb-pad locomotion and Teleport need a single hand-held controller, and the TriggerWalking needs two hand-held controllers.

Our rationale for the locomotion techniques for M-Travel mode is that Bozgeyikli reported Teleportation as comfortable and efficient for travelling in the presence of few obstacles, and so we chose this technique for the long-distance task [24]. Thumb-pad walking with tunnelling effects and the slower speed is used for the medium-distance task since it was found easy to use and learn [45]. If there is poor visibility due to walls and turns, Teleportation was found to increase spatial disorientation [24], but TriggerWalking has been shown to be efficient and realistic for small-space navigation, so it was chosen for the short-distance task [134].

5.3.4 Locomotion Methods

This section explains the implementation of locomotion techniques used in our experimental setup. We used the HTC Vive hand-held controllers for Thumb-pad locomotion, Teleportation, and TriggerWalking. The direction and speed settings are summarised in Table 5.1.

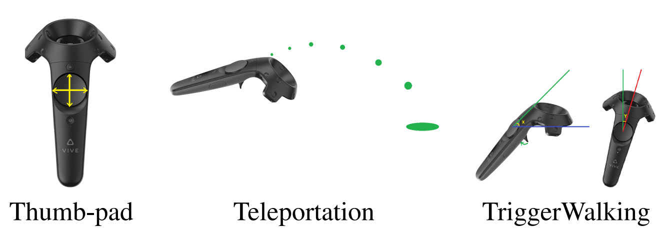


Figure 5.1: Locomotion Methods

Vive Thumb-pad Locomotion

Thumb-pad locomotion (similar to a joystick condition [87]) enabled the user to move in the environment by touching the Thumb-pad in the direction of the desired movement as shown in Figure 5.1, similar to joystick navigation controls. The further the thumb was from the centre of the Thumb-pad, the faster the user moves. The maximum speed was set to 1 m/s, similar to Kitson et al. [77] for the medium-distance task condition and to 2 m/s for the long-distance task condition. We chose to use Thumb-pad locomotion instead of a joystick to avoid having to switch devices between experimental trials, which might have caused breaks in presence. To avoid discomfort due to cybersickness, we included a tunnelling effect, whereby faster movement made the field of view shrink and vice versa, which has been shown to reduce the effects of cybersickness [45].

Teleportation

In this technique, when the Thumb-pad was pressed, a parabola was projected out of the controller and onto the ground, indicating the destination point. When the Thumb-pad was released, the viewpoint of the participant changed to the target destination. The maximum range if the teleportation is 20 m. An increase in the angle of elevation of the controller increased the range of the parabola and thus the distance to travel. The projection on the ground was green for the areas for which navigation was allowed (e.g., roads, grass), and turned red if the target location was placed on areas where navigation was not allowed (e.g., walls, objects, trees).

TriggerWalking

TriggerWalking (TW) used two HTC Vive hand-held controllers to mimic the mechanics of human bipedal walking in VR. Each hand controller is analogous to a leg, and each trigger pull moved the user one step. The direction of the movement was the average of the yaw (rotation about the up-axis) direction of the controllers, and unlike gaze-directed locomotion techniques, giving the user the ability to move in one direction and look in another. In human walking, a human can either increase the frequency of stepping or take longer strides to move faster. A similar concept was used to manipulate the speed of movement in TriggerWalking. The speed of movement could be increased by increasing the frequency of trigger pulls, or by increasing the tilt angle (angle to the ground plane) of the controller. The maximum angle to which the velocity was scaled was 90^o, and if the angle was greater than 90^o, the maximum speed was clamped to 2 m/s. The increase in speed was linear and proportional to the elevation angle. The average speed used in TriggerWalking was 0.70 m/s [134].

Tech	Direction Control	Speed Control
T-pad	Direction of Thumb from the center of T-pad	Displacement from center of T-pad capped at 2 m/s
Tele	Yaw of the controller	Instantaneous with infinite speed
TW	Average of yaw of the controllers	Tilt angle capped at 2 m/s

Table 5.1: Direction and Speed control of Tpad, Tele, and TW

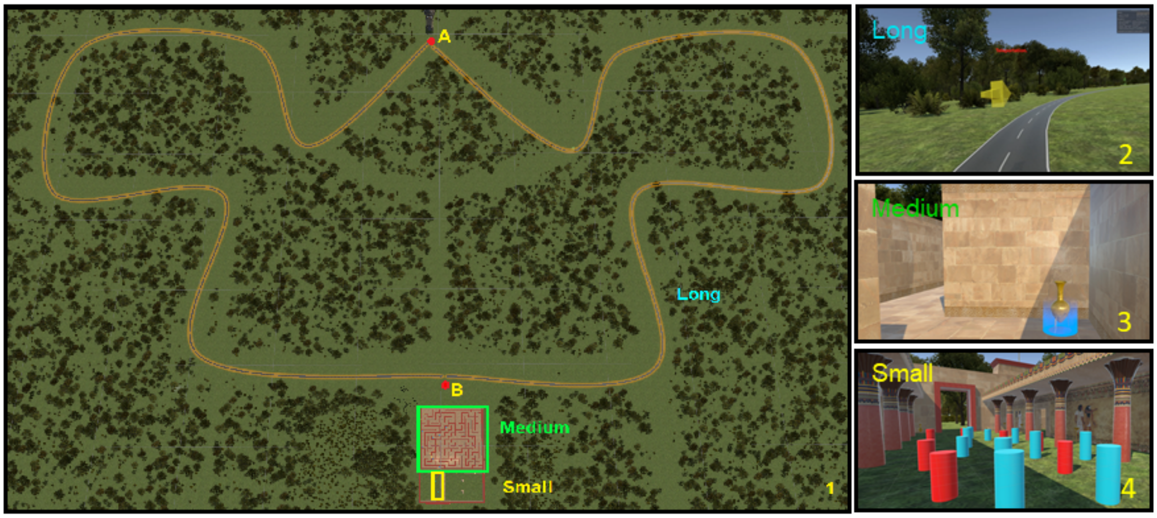


Figure 5.2: (1) The Testbed environment LUTE, with large, medium, and small environments. The highlighted orange line represents the two roads from A to B in the large environment requiring (2) long-distance travel along a long narrow road. The green rectangle represents the medium environment requiring (3) medium-distance travel through a maze with target vases to collect. The yellow rectangle represents the small environment, requiring (4) short-distance travel within a small space with red and blue cylindrical objects to collect (blue) or avoid (red).

5.4 System Overview

5.4.1 Equipment

The evaluation of M-Travel took place in a 7m×5m laboratory room space. Participants wore an HTC Vive HMD with a resolution of 1080×1200 per eye, a field-of-view of 110° and a frame rate of 90Hz. Lighthouse trackers were used to tracking the headset and controllers. We used a computer with an Intel Core i7-6700 processor, 16GB of main memory, and an NVIDIA GeForce GTX 1080 graphics card.

5.4.2 Software

The Unity3D engine version 2017.4.3 was used to render the virtual environment. GAIA[1] was used to generate a large environment, and the medium and small environment 3D assets were imported from the Unity asset store. We used LUTE (Locomotion Usability Test Environment) as the software framework for the experiment discussed in the previous chapter.

[1] http://www.procedural-worlds.com/gaia/

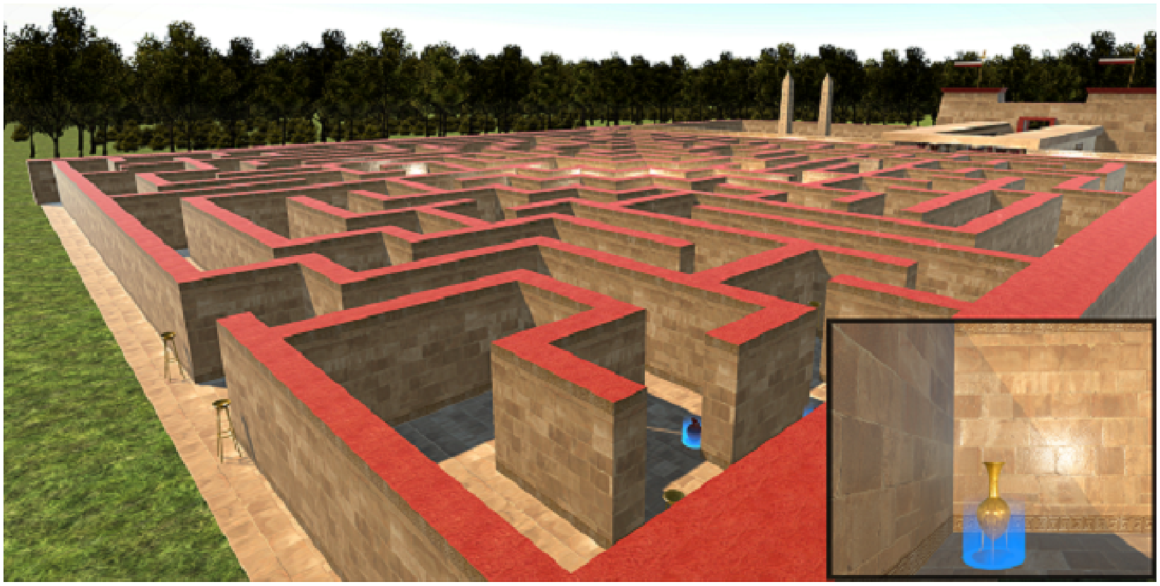


Figure 5.3: Medium Environment: Maze with target vase to collect (inset)

5.4.3 Virtual Environment

The experiment environment consisted of a large environment of size 2000m×2000m, similar to Chapter 4. Figure 5.2 (1) shows the screen-shot of half of the environment we have used in the experiment. In the middle of the environment, there was a tall tower (Point A) to give participants a landmark. For the long-distance task, we generated two 1m wide roads with six bends and a length of 1,500m from point A to B, as indicated by the orange in Figure 5.2. Only one road is displayed, and the roads were switched to mitigate the effect of the direction the user initially navigates. The environment included vegetation (grass, shrubs, bushes, and trees), as shown in Figure 5.2 (2). For the medium-distance task, a maze was set up with a 300m long and 3m wide path. The walls had a stone texture, and the maze had a number of bends and dead ends, as shown in Figure 5.2 (3). A total of 20 highlighted vases were placed throughout the maze. At the end of the maze, there was a 20m×10m area that included 20 blue and 20 red cylinders positioned between 0.7m and a minimum of 0.4m apart (Figure 5.2 (4)). The short-distance task used this space with pillars and objects in addition to the cylinders.

5.5 Study Design

To evaluate the performance, usability, and comfort of M-Travel mode, Thumb-pad locomotion, and Teleportation, we conducted a 3×2 mixed-factorial experiment with two independent variables *Locomotion Technique* (M-Travel, Thumb-pad, Teleportation) and *pose* (Sitting, Standing). The experimental design was approved by the Human Ethics Committee of the University of Canterbury. Each participant was randomly assigned to one of the following three between-subjects conditions:

1. *M-Travel mode (M-Travel)*: The participants were assigned a locomotion technique depending on the tasks, i.e., Teleportation for long distances, Thumb-pad for medium distances, and TriggerWalking for short distances.
2. *Thumb-pad (TPad)*: The participants were allowed to use only Thumb-pad during all tasks.
3. *Teleportation (Tele)*: The participants were allowed to use the only Teleportation during all tasks.

Each participant had to complete the tasks both sitting and standing. We used a counter-balanced Latin Square on the pose in order to avoid ordering effects.

1. *Sitting*: The participants performed the task with one of the locomotion techniques while sitting on a rotating and tiltable chair. No data from the chair was used in the locomotion interfaces for either direction or speed.
2. *Standing*: The participants performed the task with one of the locomotion techniques while standing in place.

5.5.1 Hypotheses

Our hypotheses were:

1. Using M-Travel mode for large, medium, and short distances will be more comfortable compared to using a single locomotion technique only (TPad or Tele).
2. Using M-Travel mode for large, medium, and short distances will be perceived as more usable compared to using a single locomotion technique only (TPad or Tele)
3. Using M-Travel mode for large, medium, and short distances will be more efficient (lower task-completion time and more objects collected) than using a single locomotion technique (TPad or Tele).
4. Sitting will be more comfortable (lower SSQ [72] and NASA-TLX [51] scores) compared to Standing for all conditions.

5.5.2 Measures

To measure subjective feelings of Comfort and Usability, we adopted previously validated questionnaires.

Comfort

We consider comfort as *"lack of unease and pain"*. Cybersickness was measured using the standard Simulator Sickness Questionnaire (SSQ) [71]. There were four values to choose from 0–3 for each question. The questionnaire was administered before the experiment and after each within-subjects condition. To measure physical and mental fatigue (workload), we used the NASA-TLX [51] in this experiment. The questionnaire was administered after each within-subjects condition.

Usability
The usability of the M-Travel mode was compared to TPad and Tele locomotion techniques using System Usability Scale (SUS) [25]. The questionnaire was administered after each within-subjects condition.

Performance
The system automatically logged the individual time taken to complete long-, medium-, and short-distance tasks, number of vases collected in the medium-distance task, number of blue and red cylinders collected in medium- and short-distance task. In addition, it also logged the number of collisions with the walls and objects in the middle- and short-distance tasks.

5.5.3 Participants

A total of 45 participants (male = 23, female = 22 , other = 0, and ages 18—45 (*M*=26.85, *SD*=5.69)) participated in the experiment. We recruited participants from the local university using on-campus fliers and posts on social network platforms. We ensured that all participants had a normal or corrected-to-normal vision. Twenty-one participants wore glasses during the experiment, and four wore contact lenses. Seventeen participants had no prior experience with 3D computer games. The height of the participants varied from 1.35—1.89m (*M*=1.68, *SD*=10.1). The total time taken for explanation, practice, task completion, filling in the questionnaires and debriefing was about 40 minutes per subject. Participants were allowed to take breaks at any time between the conditions or during the experiment if they felt uncomfortable or needed a rest.

5.5.4 Experiment Procedure

Pre-Experiment

Participants were given an information sheet outlining the experiment, which was also explained by the experimenter. Participants had to sign the consent form before filling in the demographic questionnaire. Before starting the first condition, the participant was asked to fill in an SSQ simulator sickness questionnaire to indicate a discomfort score, which acted as a baseline. Before commencing the actual tasks, the participant was informed that they could stop the experiment at any point if they felt uncomfortable or sick.

Procedure

Depending on which locomotion technique the participant was assigned to (M-Travel, TPad or Tele), a practice session helped instruct the participant how to move around a simple environment. The practice session lasted around 5 minutes for each technique. The participants were trained until they were comfortable using the locomotion technique. The participants were not trained to proficiency. A message was displayed explaining the first task, and the participant pulled the trigger to start the task. For the first task, the participant had to move along a narrow road, following a guiding arrow, as shown in Figure 5.4, in order to reach six checkpoints

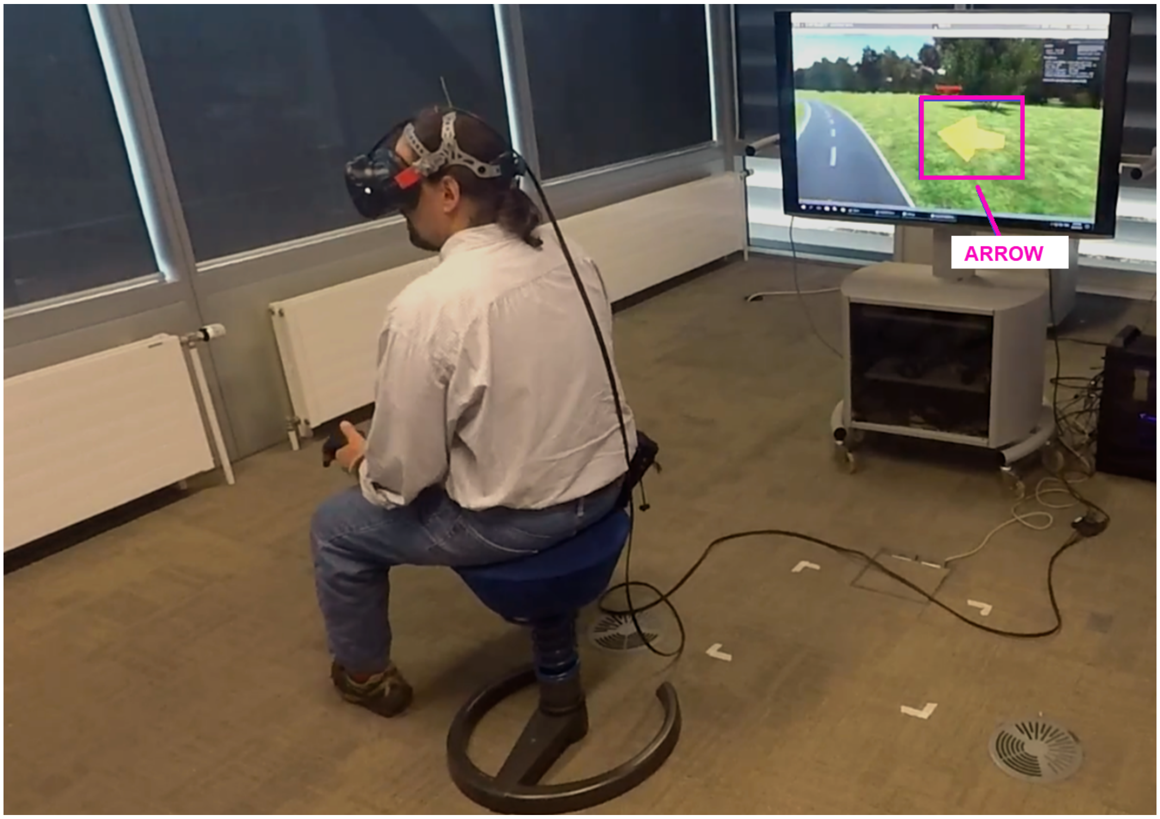


Figure 5.4: Seated user with arrow guiding through the long-distance task

indicated by green cylindrical highlighted areas. After reaching the final checkpoint, the participant was directed to enter a medium-size semi-indoor maze with turns.

A message was displayed instructing user to collect as many vases as possible, and the collection score was displayed in the HMD. Twenty highlighted vases (treasures) were placed in the maze as shown in Figure. 5.3, inset. The participant had to carefully look around to locate them, and then reach out to ”touch” them with the controller to collect them. Participants were warned prior to the study to avoid bumping into walls, and the view in the headset faded to remind them whenever they hit a wall. The arrow guided them through the maze, and participants were given three minutes to complete the task. After collecting as many vases as possible within the limited time, they were teleported to the end of the maze.

At the end of the maze, the participant was instructed to perform the short-distance task which was to move through blue cylinders to collect them, and avoid red cylinders as shown in Figure. 5.2 (4). The collection score was displayed to the participant, and they had to reach all 12 blue cylinders within one minute. Once done, a message was displayed to take off the headset, and the participant was instructed to complete SSQ,

Table 5.2: Mean SSQ scores

SUS	**M-Travel**			**Tpad**			**Tele**		
	Base	Sit	Stand	Base	Sit	Stand	Base	Sit	Stand
M	3.47	17.1	25.9	2.4	37.93	50.76	4.99	23.69	18.2
SD	5.5	12.4	18.4	4.3	36.7	42.6	6.6	25.5	23.1

SUS, and NASA-TLX questionnaires on computer. When the questionnaire was completed, the user then repeated the second pose condition using the same locomotion technique, and was asked to fill in the same questionnaires again.

Post-Experiment

At the end of the whole experiment, we administered a post-experiment questionnaire about preference, the reasons for their preferences, and any comments they wanted to provide.

5.6 Results

5.6.1 Statistical Analysis

The data were analyzed with SPSS using a mixed ANOVA. The statistical significance level was set to $\alpha = 0.05$. Normal distribution of the data was assessed with a Shapiro-Wilk test. When the data were non-normal, an Aligned Rank Transformation was applied. When a pair-wise comparison was carried out, Bonferroni correction was applied to counteract inflated Type I errors due to multiple comparisons. Two participants, one in the TPad and one in the M-Travel conditions, experienced nausea and did not complete the study. Their data were not included in the statistical analysis.

5.6.2 Comfort

Cybersickness
Figure 5.5 shows the mean SSQ scores by condition. We compared baseline(pre-experiment), sitting, and standing SSQ scores. There was a significant main effect of pose on the total SSQ score, $F(2,80)=3.482$, $p=0.035$. There was also a significant main effect of locomotion technique on SSQ scores $F(2,40)=3.68$, $p=0.034$. Post-hoc tests showed that there was a significant difference in SSQ scores between TPad and Tele ($p=0.015$).
Work Load
NASA Task Load Index (NASA-TLX) was used to compare the Physical, Mental, and Temporal demands of tasks for different pose and locomotion techniques. Table 5.3 lists the mean and standard deviation values

Figure 5.5: Mean SSQ scores (Base, Sitting, and Standing)

of NASA-TLX question scores of M-Travel, TPad, and Tele conditions for different poses. The questions in the NASA-TLX indicated Mental Demand, Physical Demand, Temporal Demand, Effort, Performance, and Frustration, respectively. They were no significant main effects of pose on Nasa-TLX. There were no significant main effects of pose on Mental Demand ($F(1,40)=3.104$, $p=0.086$), Physical Demand ($F(1,40)=1.379$, $p=0.264$), Temporal Demand ($F(1,40)=1.515$, $p=0.232$), Effort ($F(1,40)=2.515$, $p=0.094$), Performance ($F(1,40)=0.317$, $p=0.730$) or Frustration ($F(1,40)=1.189$, $p=0.315$) for the tasks. There were no significant main effects of locomotion technique on Mental Demand ($F(2,40)=0.10$, $p=0.99$), Physical Demand ($F(2,40)=1.793$, $p=0.18$), Temporal Demand ($F(2,40)=0.807$, $p=0.453$), Effort ($F(2,40)=0.478$, $p=0.624$), Performance ($F(2,40)=0.234$, $p=0.793$) or Frustration ($F(2,40)=0.317$, $p=0.730$) for the tasks.

5.6.3 Usability

There were no main effects for pose on the SUS $F(1,40)=0.087$, $p=0.769$, for locomotion techniques $F(2,40)=1.331$, $p=0.276$.

Performance

The mean and standard deviation values of Task Completion Time, Collection Score and Collisions are summarized in Table 5.5.

Table 5.3: Mean NASA-TLX scores

NASA-TLX	M-Travel		Tpad		Tele	
	Sit	Stand	Sit	Stand	Sit	Stand
Mental Demand (M)	57.6	51.9	63.4	48.9	54.5	54.3
SD	19.50	26.29	20.82	28.36	33.78	27.69
Physical Demand (M)	24.4	24	25.2	25.8	32.7	43.1
SD	24.39	18.92	17.46	22.09	28.53	28.14
Temporal Demand (M)	37.8	44.4	42.4	36.1	48	51.9
SD	26.47	24.59	26.91	23.94	31.73	23.75
Effort (M)	71.4	81.1	69.5	76.3	72.1	67.6
SD	13.01	12.27	23.63	15.46	23.54	25.58
Performance (M)	50.8	46.9	54.2	54.6	53.3	55.5
SD	22.72	26.90	26.39	30.90	31.25	23.83
Frustration (M)	32	31.6	30.3	25.6	33.7	37.5
SD	24.27	28.34	26.05	25.52	26.98	29.20

Table 5.4: Mean SUS scores

SUS	M-Travel		Tpad		Tele	
	Sit	Stand	Sit	Stand	Sit	Stand
M	80.2	79.5	69.5	73.2	76.5	74.8
SD	12.77	17.84	16.24	14.80	11.29	16.20

Task Completion Time

There were no significant differences between the task completion times for the locomotion techniques for Long (F(2,40)=0.214, p=0.813), Medium (F(2,40)=1.098, p=0.385), and Short (F(2,40)=0.305, p=0.746) tasks. No significant differences were identified between task completion time for Long (F(2,40)=2.161, p=0.186), Medium (F(2,40)=0.062, p=0.94), and Short (F(2,40)=0.081, p=0.923) tasks in either Sitting or Standing conditions.

Collection Score

Since the Long-distance task did not involve collecting objects; there are no collection scores for it. The statistical analysis indicated no significant differences between the collection scores on the Short-distance task for different locomotion techniques (F(2,40)=0.008, p=0.99). There was a significant difference between the collection scores of the Short-distance task between Sitting and Standing (F(1,40)=8.78, p=0.21) when we did

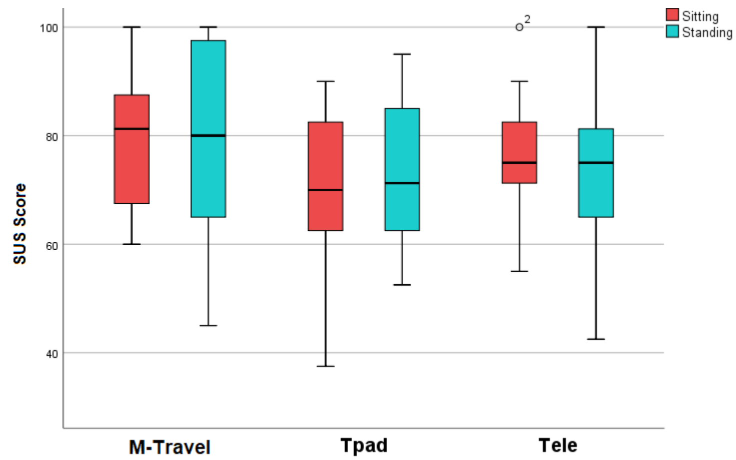


Figure 5.6: SUS Box plots. The whiskers represent max and min SUS scores

Table 5.5: Mean task completion times #T (seconds), collection scores #S, and collisions #C

LUI	*#T* **Long (s)**		*#T* **Medium (s)**		*#T* **Short (s)**		*#S* **Medium**		*#S* **Short**		*#C* **Wall**	
	Sit	Stand	Sit	Stand	Sit	Stand	Sit	Stand	Sit	Stand	Sit	Stand
M-Travel (M)	147.1	155.4	180	180	60	60	16	14.6	16	13	2.5	5
SD	12.09	25.21	0	0	0	0	4.58	0.58	4.58	4.5	0.7	1.42
Tpad (M)	151.50	172.7	171.7	180	53.7	60	19	11.5	17	13.5	18.5	9
SD	29.63	27.24	9.5	0	7.18	0	1.86	3.6	3.25	7.09	23.3	7
Tele (M)	123.5	119.7	180	167.8	55.9	55.4	13.6	14	15.6	16.3	24.2	32.8
SD	40.99	41.06	0	11.39	7.06	7.82	6.51	4.58	5.86	6.35	22.35	45.69

not consider the locomotion technique as a factor.

Collisions

Mean wall collisions are reported in Table 5.5. There were no significant effects of locomotion technique (F(2,40)=0.99, p=0.42) or pose (F(1,40)=0.06, p=0.8) on wall collisions. There were no significant interaction effects for wall collisions between locomotion technique and pose (F(2,40)=0.57, p=0.58).

5.6.4 Preference

To find the subjective preference of the participants for pose, we asked the participants to indicate their preferred pose between the sitting and standing. Out of 14 participants who were assigned to the TPad condition to complete the tasks, 78.57% (11) preferred sitting, and 21.42 % (3) preferred standing. Out of 15 participants who were assigned to the Tele condition, 33.33 % (5) preferred sitting, and 66.66%(10) preferred standing. Out of 14 participants who were assigned to the M-Travel condition, 42.85% (6) preferred sitting,

Table 5.6: Participant Comments

Locomotion Technique	**Pose**	**Preference**
M-Travel	Sitting	Feels more secure and easy Sitting gave extra stability and comfort
	Standing	Sitting increased nausea I can control the body well while standing
Tpad	Sitting	Easier to rotate the body More comfortable Don't have to be worried about balance
	Standing	Comfortable to move around the environment Felt more focused on my way and destination It is not real to sit and walk in the scenario
Tele	Sitting	Felt less balanced especially in the maze Easy to rotate around and comfortable Do not have to worry about tripping over the headset chord
	Standing	Standing is easier to change directions Feels harder to move in VE while sitting Standing condition felt more real although I did better in sitting condition

and 57.14% (8) preferred standing. The chi-square goodness-of-fit test indicated that the participants preferred sitting in the TPad condition significantly (χ^2=4.571, p=0.033).

In addition to preference, we asked participants for the reasons behind their preference and obtained feedback as shown in Table 5.6. Most of the participants who preferred standing reported that standing made them feel more immersed compared to sitting.

Looking at the preferences of the participants, they favour Sitting in the TPad condition. A majority of participants indicated that standing made them uncomfortable during the TPad condition. One participant commented that he felt nauseous using Teleportation while sitting. For the Tele condition, a majority of participants indicated that they preferred standing since it gave them more flexibility to move around the virtual environment.

5.7 Discussion

The discussion that follows is organized first around four hypotheses laid out in Section 5.5.1. *Hypothesis 1* states that *Using M-Travel mode for large, medium, and short distances will be more comfortable compared to using a single locomotion technique only (TPad or Tele)*. Statistical analysis shows that the Tpad condition induces more cybersickness than Tele. This supports the findings from previous studies [87, 37, 134]. There was no difference in perceived workload measured using NASA-TLX. Results did not show that M-Travel mode has less perceived cybersickness or work load than Tpad and Tele and hence *Hypothesis 1* was not confirmed.

Hypothesis 2 states that *Using M-Travel mode (M-Travel) for large, medium, and short distances will be perceived as more usable compared to using a single locomotion technique only (TPad or Tele).* The SUS results of the M-Travel mode were not statistically different from the other locomotion techniques (TPad and Tele). Hence *Hypothesis 2* was not confirmed. However, using the SUS score scale proposed by Bangor et al. [7], the usability of M-Travel (Sit: 80.18, Stand: 79.46), and Tele (Sit: 76.50, Stand: 74.83) is between Good-Excellent and Tpad (Sit: 69.47, Stand: 73.21) is between Ok-Good.

Hypothesis 3 states that *Using M-Travel mode for large, medium, and short distances will be more efficient (lower task-completion time and more objects collected) than using a single locomotion technique (TPad or Tele).* Participant collection scores were higher while standing compared to sitting, and there were no significant differences in collection scores for different locomotion techniques. One reason the collection scores were different could be because of the differences in eye height while sitting and standing. According to Leyrer et al. [92, 93] standing for locomotion is more natural, and the eye height affects the distance estimation in VR. A reason for not getting a significant difference could be the time constraint in the various tasks (the score of the participants had a ceiling effect). Participant performance showed that there were no significant differences in the task completion times and collisions for pose or locomotion technique. Hence *Hypothesis 3* was not confirmed.

Hypothesis 4 states that *Sitting is comfortable (less cybersickness and less fatigue) than standing in VE exploration tasks.* Participants standing reported more cybersickness scores compared to the sitting. This might be due to the less frequent body and head movement while sitting, which in turn reduces cybersickness as already reported in a study by Arcioni et al. [3]. Hence *Hypothesis 4* was confirmed. Participant preference confirms that participants preferred sitting compared to standing in the TPad condition. This could be because of minimal head and body movement in sitting than standing [3]. It is interesting to see that in Tele condition, people preferred standing. Previous literature has stated that Teleportation performance is low when there are low visibility [24]. Also, the eye height affects the perception of spatial layout in Virtual Environments [93] and this might be the contributing factor for participants preference.

5.7.1 Limitations

The M-Travel mode implemented for this experiment does not allow participants to switch to a locomotion technique they prefer. The locomotion techniques were chosen for each task based on reports in the literature of their performances in tasks similar to those we implemented in this experiment. Though the participants had a short training session before starting the experiment, there were no measures used to check their proficiency in using the three locomotion techniques. Ruddle et al. [133] found that there is a direct correlation between training the participants to proficiency and their performance in using locomotion techniques to complete a set of tasks. Hence, it is hard to predict their rational preference in choosing a better technique. For example, some techniques might be easy to learn, but not comfortable to use, and some techniques might need some initial training and might be more suitable and comfortable for the task. We did not train the participants long enough to check their proficiency in this case. Time constraints add cognitive load while completing a task and is used in many tasks in games [145]. In our trials before the actual study with our colleagues, they could complete the medium- and short- distance tasks before the allocated times. However, in the experiment, some participants could not finish the medium-distance task in the allocated time.

5.8 Summary of the Study

We introduced M-Travel mode that uses different locomotion techniques based on locomotion tasks. We compared it with Teleportation (Tele) and Thumb-pad (TPad) locomotion to evaluate the comfort and performance of the method. We designed a study to include tasks which required long-, medium-, and short-distance travel. We found that TPad induced more cybersickness than Tele, which supports previous findings in the literature [87, 36, 134]. Based on participant preferences and the SSQ scores, we found that sitting is more comfortable when using TPad locomotion than standing.

Secondly, the system did not allow participants to choose between locomotion techniques to complete a task. We speculate that if the participants could switch or choose a locomotion technique according to their preference in a given scenario and task, this may influence their performance.

An ideal solution to the current issues in locomotion is to develop a comprehensive locomotion system which gives the user the ability to choose a comfortable and efficient way of navigating through a virtual environment depending on the task, pose, personal preference, size of tracked space, and size of the virtual environment. To fully understand the performance and usability of giving a choice of switching between different locomotion techniques, we conducted a user study described in the next chapter. Prior to the evaluation, we trained the participants in all the techniques included in the M-Travel mode. The details of user study setup, implementations, and results are discussed in the next chapter.

Chapter 6

Multi-Travel mode (User-selected)

In the previous chapter, we discussed the implementation and evaluation of Multi-Travel mode (M-Travel mode) with pre-selected locomotion techniques. The analysis of the results shows no significant improvement in performance when M-Travel mode is used compared to using single locomotion techniques (Teleportation and Thumb-pad navigation). In this chapter, we discuss the implementation of M-Travel mode when user is free to choose locomotion technique among Teleportation (Tele), TriggerWalking (TW), and Walking-in-Place (WIP). In this mode, users have the choice of choosing/switching locomotion techniques based on their preference. We conducted a user study to observe the behaviour and preference of participants for three levels of distance and clutter (obstacles in VE).

6.1 Locomotion Methods

The rationale for including Teleportation and TriggerWalking in M-Travel mode and their implementation are discussed in detail in the previous chapter. We included WIP as another locomotion choice in M-Travel mode. The rationale and implementation are discussed below.

6.1.1 Walking-in-Place

WIP provides real walking gestures that provide vestibular feedback resulting in lower cybersickness scores. Studies evaluating WIP compared to other artificial travel techniques showed that it is more natural, and users feel more present in the VE. However, WIP can cause fatigue if used for travelling longer distances in VE [157].

In the WIP condition, two Vive trackers [1] were attached to feet. The trackers give the information on the height of the foot during walking steps. The direction of movement was an average of the forward direction of both trackers. The speed of the movement was scaled between the average speed of 0.70 m/s and maximum

[1] https://www.vive.com/nz/vive-tracker/

speed 2 m/s based on the foot height. The average and maximum speed are the same as that of TW. Before using WIP, the foot height of the user was calibrated in a rest position to get the minimum foot height at rest. The maximum foot height was clamped at 0.2 m above the rest height. This implementation is similar to SAS-WIP [29], however the threshold values for the step detection and the speed has been changed based on our pilot trials.

6.2 Study Design

We conducted a user study to understand the preferences of participants in choosing or switching between locomotion techniques. The study had two sessions over two consecutive days to avoid confounds from learning effects. The first session was for training, with the goal of getting participants to a defined level of proficiency or competency with all the techniques. In the second session, we introduced M-Travel mode that has a suite of locomotion techniques: Tele, TW, and WIP. M-Travel mode allows participants to switch between different locomotion techniques based on the travel distance, environment complexity, personal preference, and the task.

6.2.1 Day 1: Training Session

In the training session, participants were trained for accuracy and speed in the three locomotion techniques Teleportation, TriggerWalking, and WIP. We assumed that proficiency in each technique would be a critical component to observe the effects of the study, as discussed by Ruddle et al. [133].

Accuracy Training

For accuracy, the virtual environment scene consisted of a red cylinder surrounded by four blue blocks of equal size and 1.25m away from the center of the red cylinder, as shown in Figure. 6.1. The task for the participant was to navigate to the centre of the red cylinder without colliding the blue blocks. The distance between the participant and the center of the cylinder was calculated for every frame. When the distance between the participant and the cylinder was less than 2m, the cylinder disappeared a new target appeared. Once the participant reached the cylinder, the cylinder disappeared, and another identical cylinder appeared at a specified distance and random angle away from the participant. There were three difficulty levels in training for accuracy and participants performed ten trials at each level. After Level 1 was completed, the radius of the red cylinder decreased by 20%. For example, from Level 1 to Level 2, the radius decreased from 2m to 1.6m, and the distance between blue blocks and the cylinder decreased by 0.25m. As the participant progressed through the levels, it became more difficult to navigate to the cylinder without touching the blue blocks. The task time and the number of collisions were noted for each trial for later analysis. After completing Level 3 in accuracy training, the participant was trained for speed.

Speed Training

Similar to the Accuracy Training setup, we trained participants for speed. The task for the participant was to reach the red cylinder as fast as possible. When the participant reached the first cylinder, another red cylinder appeared at a specified distance and random angle away from the participant. Again, the distance was set according to locomotion technique using values (Tele = 15m, TW = 8m, and WIP = 5m). Similar to accuracy training, there were three distance levels, and after the participants completed the first level, the cylinder distance increased by 25% of the previous distance. For example, the target distance for Teleportation increased from 15m (Level 1) to 18m (Level 2). The task time was noted for each of 10 trials at each of three levels. The data was logged for training proficiency analysis.

In speed training, we logged the time taken for each trial to see if their performance met our pre-established proficiency threshold of four minutes (automatically logged) for each difficulty level. The threshold is set based on the average time taken by the participants in the consultation before the actual user study. The participants were four researchers in HIT Lab NZ. We also asked participants to tell us their subjective feeling about their proficiency for each of the three travel techniques. If a participant's subjective feeling was not confident in any locomotion technique, he/she was asked to practice the locomotion technique in practice environment until the participant was confident. We would have repeated the training session if a participant failed to meet the threshold requirement, but all participants met the proficiency threshold after the training session and also indicated confidence in using the travel techniques at the end of the training.

6.2.2 Day 2: Testing Session

Before the testing session, we let participants practice all three locomotion techniques they learned in Session 1 in the practice environment shown in Figure. 6.2. After the participants reported they were confident with all the three locomotion techniques, they proceeded to the accommodation Session.

Accommodation Session

The accommodation Session aimed to study the participants' choice of travel technique for simple locomotion tasks for three levels of distance and clutter. The task was to travel to a blue cylinder displayed in front at different distances for each condition (short, medium, and long-distance) and come back to the original starting point (indicated by another square blue cylinder) using their preferred travel technique. There were three variations in distances (short (50 m), medium (100 m), and long (150 m)) and three variations in the amount of clutter (low, medium, and high), resulting in nine environment conditions. Each condition had three trials, resulting in a total of 27 trials for each participant. The nine environment conditions were randomized using balanced Latin square [2]. We recorded the time taken for the participant to travel from the starting position, go to the target position, and come back to the original position, the number of collisions with objects in the VE, participant location data (x, y, and z coordinates), and locomotion technique being used in each frame of session. We recorded the screen capture of the session to further analyze the participant's behaviour for varying degrees of distance and clutter.

Final Testing Session

The experiment included long-, medium-, and short-distance tasks similar to the user study discussed in chapter 5. In this session, the participant could use any travel mode available in M-travel mode to complete the tasks. For the long-distance task, the participant had to follow the road to the entrance of the maze. The medium-distance task included collecting 12 vases while navigating through the maze. The participant had to move near (<0.01m) each vase for it to be automatically collected. In the short-distance task, the participant had to touch blue cylinders (touching using controllers or move very near to the cylinders) while avoiding collisions with red cylinders.

6.2.3 Hypothesis

Given that the participants were proficient in all the locomotion techniques, our hypothesis was *"M-Travel mode is a novel locomotion interface that is comfortable and usable"*.

6.2.4 Measures

We used similar measures for Comfort and Usability as in the previous study in Chapter 6.
In addition, we included a custom questionnaire in each session that participants answered in the computer.

Training Session:

- A five-point scale to measure subject rating of proficiency (0: Definitely yes, 4: Definitely not).
- Technique preferred.

Testing Session:

- Technique preferred and the reason behind the preference.
- A five-point scale to measure the subjective effort of switching locomotion (0: Very easy, 4:Very hard).
- Any issues while doing the task.

In addition to this questionnaire, there was an informal interview at the end of the experiment. The interview questions were:

[2] https://statpages.info/latinsq.html

Table 6.1: Measures used in the experiment

Session	Quantitative	Qualitative
Accuracy Training	-Time taken per trial -Obstacle Collision Score	-Proficiency Self Rating
Speed Training	-Time taken per trial	-Proficiency Self Rating
Pre-Experiment		-SSQ
Accommodation Session	-Time taken per trial -Obstacle Collision Score	-SSQ -IPQ Presence Questionnaire -NASA-TLX -SUS
Testing Session	-Time taken for long, medium, and short distance tasks -Medium task score -Wall Collisions -Short task Collisions	-SSQ -IPQ Presence Questionnaire -NASA-TLX -SUS
Post-Experiment		-Preference -Interview Questionnaire

- Was there a strategy you used in choosing locomotion techniques to complete the task?
- Did you think much before switching to another locomotion technique or was it instantaneous?

6.2.5 Participants

Eighteen participants (male = 6, female = 12, other = 0) took part in the study and completed both the training and testing sessions. The age of the participants ranged from 18 to 34 years (M = 24, SD = 4.23), and all had a normal or corrected-to-normal vision and had no reported balancing issues. All participants were recruited via social media posts and advertisements on billboards on campus. Participants were compensated with a gift voucher. Participants were warned about cybersickness and were asked to inform the researcher if there was any slight discomfort. A chair was provided to rest in case they felt tired at any time during the session. The experiment was approved by the Human Ethics Committee of the University of Canterbury.

6.2.6 Experimental Procedure

The experiment was divided into two sessions:

Day 1: Training Session

Each participant took approximately 45 minutes to complete the pre-training, training, and post-training practice sessions. Participants answered all the questionnaire in Qualtrics on a computer.

Pre-Training

The participant was given an information sheet outlining the experiment, and the experimenter also explained the experiment procedure. The participant had to sign the consent form before filling in the demographic questionnaire. After completing the questionnaire, the researcher explained the training conditions and levels.

Training

The locomotion conditions were randomized across participants to balance for learning effects. Depending on the locomotion order assigned, the participant went through accuracy and speed training. After training for their first locomotion condition, the participant was asked to fill in a proficiency self-rating questionnaire and then moved on to training for the next locomotion technique. Similarly, for the third locomotion condition, they trained, and filled in a proficiency self-rating questionnaire.

Post-Training Practice

If the participant was not confident in any locomotion technique, he/she was encouraged, but not required to practice the locomotion technique until feeling proficient using the locomotion technique. The realistic practice VE as shown in Figure 6.2

Day 2: Testing Session

Each participant took approximately 40 minutes to complete pre-experiment, practice, accommodation, testing, and post-training sessions.

Pre-Experiment

Before starting the experiment, the participant was asked to fill in an SSQ Cybersickness questionnaire to indicate a discomfort score. This score acted as a baseline. Before commencing the actual tasks, the participant was informed that they could stop the experiment at any point if they felt uncomfortable or sick.

Practice Session

The participant was asked to practice the three locomotion techniques Teleportation (Tele), TriggerWalking(TW), and WIP in the practice environment shown in Figure 6.2 until they felt confident again in using them.

Accommodation Session

After the participant put on the HMD, and there was a single practice trial to understand the task of travelling to the target position and coming back to the starting position. A message displayed the trial number at the starting position. After the participant reached the target, another message was displayed explaining to go back to the original position. After completing the accommodation session, the participant was instructed to complete the SSQ, SUS, IPQ presence, and NASA-TLX questionnaire. The participant was encouraged to take a 5-minute break.

Testing Session

At the beginning of the testing session, a message was displayed explaining the task. For the long-distance task, the participant had to move along a narrow road to the entrance of a maze. After reaching the entrance of a maze, a message was displayed to collect vases. The participant was warned prior to the study to avoid bumping into walls, and the view in the headset faded to remind them whenever the participant hit a wall. The participant had to go through the maze to the entrance of a small space with 20 blue and 20 red cylinders. A message was displayed to touch or collide with all the blue cylinders and avoid red cylinders. The cylinders disappeared as soon as the participant touched them. After all the 20 blue cylinders disappeared, a message was displayed instructing the participant to remove the HMD. Afterwards, the participant was instructed to complete SSQ, SUS, and NASA-TLX questionnaires.

Post-Experiment

At the end of the whole experiment, we provided a post-questionnaire relating to preference, the reasons for their preferences, and any comments they wanted to include. Also, there was an interview to find the participant's strategy in switching between the locomotion techniques and to understand their opinion on ease of switching.

6.3 System Overview

The equipment, software and testing environment used were similar to the user study described in chapter 5 (section 2). In addition to the VE used in the user study in Chapter 5, we developed environments for training, practice, and accommodation sessions described below.

6.3.1 Experiment Environments

Training Environment

Figure 6.1 shows the accuracy training and speed training VEs. The virtual training environment consisted of a plain green grass field with a red cylinder (diameter = 2m). For accuracy training, the cylinder was surrounded by four transparent blue cubes (length = 1m) whose center is 1.25m away from the center of the cylinder. The speed training environment just had a red cylinder without any other objects.

Practice Environment

The practice environment was set up to practice any travel technique that participant was not confident after the training session on Day 1 and to remember all the travel techniques learned on Day 1. The practice environment was also used before the accommodation and training sessions on Day 2. The practice environment was a Unity asset NVIDIA Viking Village[3], as shown in Figure 6.2. This environment consisted of realistic outdoor

[3]https://assetstore.unity.com/packages/templates/tutorials/nvidia-viking-village-88651

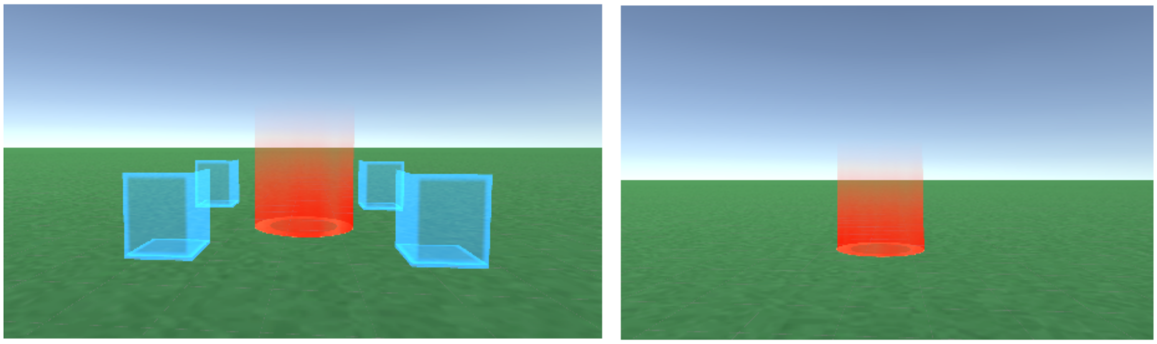


Figure 6.1: Accuracy training VE Speed training VE

and indoor setup in which participants could navigate using any of the available travel techniques without any time constraints.

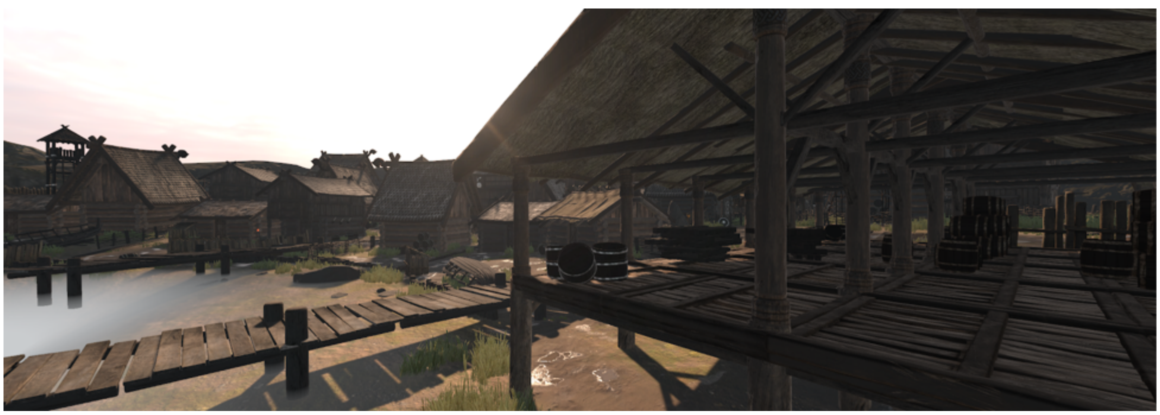


Figure 6.2: Practice Environment : Outdoor Viking village environment

Accommodation Environment

The accommodation session aimed to help participant and researcher understand their preference in using travel techniques for different levels of distance and clutter. For example, in a condition where there is a clear view of the target, the participant might first use TW but might switch to Tele in second or third after finding TW takes more time. The virtual environment had a long hall with a target (blue square cylinder) at a distance. The route had variable amounts of clutter (vases, rectangular boxes, and plants). Figure 6.3 shows the accommodation VE for low clutter, short-distance condition. In Figure 6.4, i.e., medium-clutter and medium-distance condition, the target is further from starting point and there is clutter, but the view to the target is not obstructed. The high-clutter and long-distance condition has high clutter that partially obstructs the view of the target as seen in Figure 6.5.

Figure 6.3: Accommodation Session VE: Low-clutter and short-distance condition

Figure 6.4: Accommodation Session VE: Medium-clutter and medium-distance condition

Figure 6.5: Accommodation Session VE: High-clutter and long-distance condition

Testing Environment

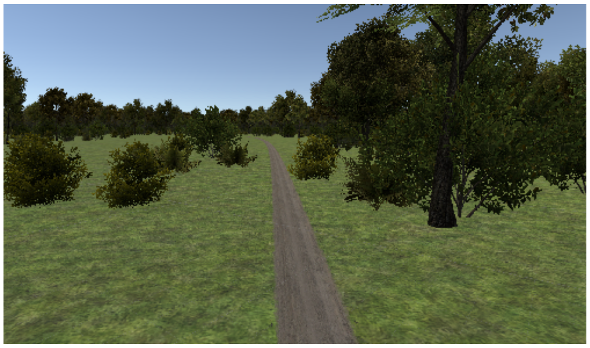
The environment consisted of a long-distance (1000m) path of 1m width road with three bends. The environment used vegetation of medium-height (grass, shrubs, bushes, and trees), as shown in Figure 6.6. In the middle of the environment, there was a tall tower to give participants a landmark in the environment. At the end of the long-distance path, a maze was set up with paths approximately 5m width and 200m length. This maze had wider paths and fewer bends and dead-ends compared to the maze in the previous user study to make the environment less complicated. The walls had a stone texture. There were 12 golden vases (treasure targets) set up in the maze. At the end of the maze, there was a small space with a 20m$\times$10m area that included 20 blue and 20 red cylinders.

6.4 Results

6.4.1 Day 1: Training Session

Statistical Analysis

The mean number of collisions in accuracy training for all locomotion conditions was less than one and hence was not further investigated. A repeated-measures ANOVA with Greenhouse-Geisser correction (if sphericity assumption was not met) was used for the parametric data, i.e., task completion time, self proficiency score.



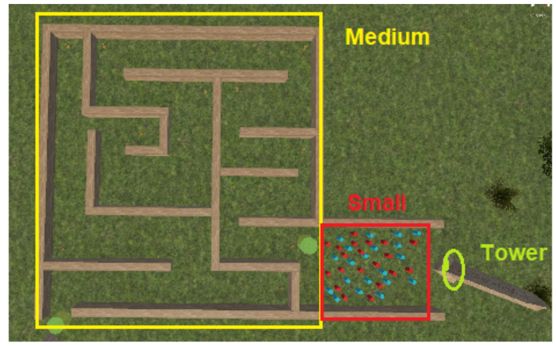


Figure 6.6: Participant view of long-distance task (Left) and top view of medium-distance, and short-distance tasks(Right)

Further posthoc tests were conducted using Bonferroni correction. For non-parametric data, i.e., participants locomotion preference over all the different conditions, we used a Chi-Square Goodness-of-fit Test. All the statistics were computed using SPSS Version 25.

To understand if the participants performance (time taken to reach the target) improve over multiple trials for the three locomotion techniques Teleportation (Tele), TriggerWalking (TW), and Walking-in-Place (WIP), we compared the time taken for the participant to complete each trial. Figure 6.7 and Figure 6.8 shows the mean time taken to complete the all three levels for each travel mode in accuracy and speed training.

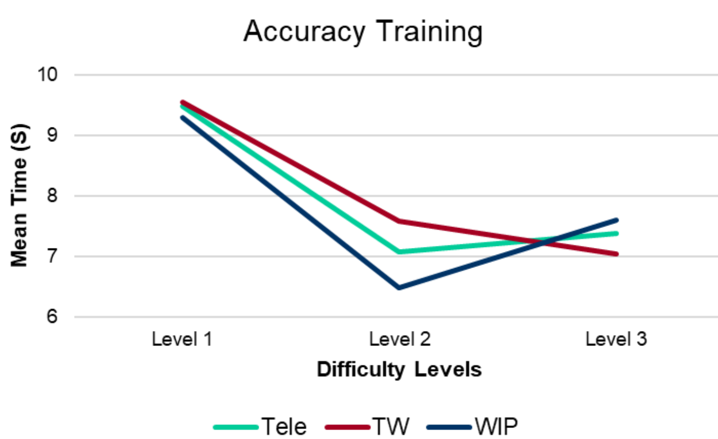


Figure 6.7: Accuracy Training

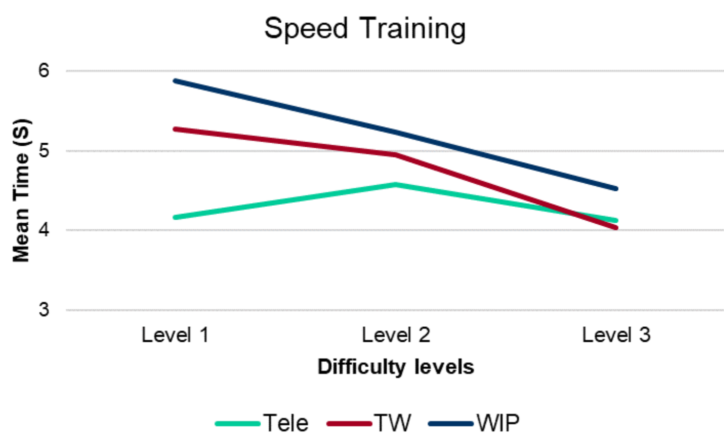


Figure 6.8: Speed Training

Teleportation

Table 6.2 lists the results of repeated measures ANOVA for accuracy training. Table 6.3 lists the results of repeated measures ANOVA for speed training. The significant values are highlighted in gray. The decrease in mean time taken to complete the over ten trials (all the three levels) of accuracy training and speed training for Tele can be seen from mean values in Table 6.2 and Table 6.3.

Table 6.2: Accuracy Training for Tele

Difficulty Levels	Mean (s)	df	F	Sig
Level 1	9.47	9	62.15	0.02
Level 2	7.06	9	33.14	0.06
Level 3	7.38	9	50.64	0.06

Table 6.3: Speed Training for Tele

Difficulty Levels	Mean (s)	df	F	Sig
Level 1	4.16	9	59.77	0.06
Level 2	4.58	9	51.06	0.07
Level 3	4.13	9	21.57	0.51

We found a statistically significant difference within task times in Difficulty Level 1 for accuracy training. There was no significant difference within task times in Difficulty Level 2 and Difficulty Level 3 for accuracy training in Tele condition. In the Tele condition, there was no statistically significant difference between speed in trials in Difficult Level 1, Difficulty Level 2 and Difficulty Level 3.

TriggerWalking

Table 6.4 lists the results of repeated measures ANOVA for accuracy training. Table 6.5 lists the results of repeated measures ANOVA for speed training. The mean time taken to complete ten trials (all the three levels) of accuracy training and speed training for TW can be seen from mean values in Table 6.4 and Table 6.5.

Table 6.4: Accuracy Training for TW

Difficulty Levels	Mean (s)	df	F	Sig
Level 1	9.53	9	42.64	0.001
Level 2	7.57	9	22.54	0.29
Level 3	7.03	9	42.33	0.35

Table 6.5: Speed Training for TW

Difficulty Levels	Mean (s)	df	F	Sig
Level 1	5.27	9	78.08	0.04
Level 2	4.94	9	153	0.85
Level 3	4.03	9	56.15	0.59

There was a statistically significant difference within task times in Difficulty Level 1 for accuracy training. There was no significant difference within task times in Difficulty Level 2 and Difficulty Level 3 for accuracy training. In TW condition, there was a statistically significant difference between the speed in trials in Difficulty Level1. There was no statistically significant difference in speed between trials for TW condition in Difficulty Level 2 and Difficulty Level 3.

Walking-in-Place

Table 6.6 lists the results of repeated measures ANOVA for accuracy training. Table 6.7 lists the results of repeated measures ANOVA for speed training. The decrease in mean time taken to complete ten trials (all the three levels) of accuracy training and speed training for WIP can be seen from mean values in Table 6.6 and Table 6.7.

Table 6.6: Accuracy Training for WIP

Difficulty Levels	Mean (s)	df	F	Sig
Level 1	9.28	9	63.88	0.31
Level 2	6.47	9	54.55	0.09
Level 3	7.59	9	50.15	0.03

There was a statistically significant difference within task times in Difficulty Level 1 for accuracy training. There was no significant difference within task times in Difficulty Level 2 and Level 3 for accuracy training. There was no significant difference within task times in Difficulty Level 1, Difficulty Level 2, and Difficulty

Table 6.7: Speed Training for WIP

Difficulty Levels	Mean (s)	df	F	Sig
Level 1	5.88	9	56.2	0.09
Level 2	5.24	9	153	0.4
Level 3	4.52	9	69.55	0.06

Table 6.8: Distance and Clutter Conditions

Cond	S-L	M-L	L-L	S-M	M-M	L-M	S-H	M-H	L-H
Distance	short	medium	long	short	medium	long	short	medium	long
Clutter	low	low	low	medium	medium	medium	high	high	high

Level 3 for speed training. In training the participants in each locomotion technique, we can see that there is significant improvement in the first level of accuracy training. There is no significant increase in performance in speed training. One reason could be that the participants learnt the locomotion technique in first difficulty level of accuracy training and didn't need more training to perform well.

Participants reported a self-rating to their proficiency in each locomotion technique after completing the accuracy and speed training. There was a significant difference between self-rating between the three conditions ($F(1.754, 29.819) = 8.098, p = 0.001$). Post hoc tests using the Bonferroni correction revealed that the self-rating for Tele was significantly higher than for WIP. The mean and standard deviation scores of self-rating were: Tele (M = 3.8, SD = 0.43), TW (M = 3.5, SD = 0.62), and WIP (M = 3.00, SD = 0.77). Fourteen participants preferred Teleportation, three participants preferred TriggerWalking, and one participant preferred Walking-in-Place. Teleportation had significantly higher preference than TriggerWalking and Walking-in-Place ($\chi^2(2) = 16.333, p < 0.001$).

6.4.2 Day 2: Testing Session

Statistical Analysis

A repeated-measures ANOVA with Greenhouse-Geisser correction (if sphericity assumption was not met) was used for the parametric data, i.e., Task completion time, the number of travel mode changes, SSQ, SUS, Presence IPQ, NASA-TLX. Further posthoc tests were conducted using Bonferroni correction. For non-parametric data, i.e., participants locomotion preference for tasks in accommodation session and final preference of the participants, we used Chi-Square Goodness-of-fit Test in SPSS. Data of one participant were excluded due to data logging errors. The conditions in the Accommodation Session were labelled, as shown in Table 6.8.

Accommodation Session

To measure the participant's performance, we measured the time taken to complete trials in the Accommodation Session. The mean and standard error values are listed in Table 6.9.

Table 6.9: Mean Task Times for Accommodation Session

Distance/Clutter	Short	Medium	Long
Low	M = 7.88 SD = 0.55	M=9.25 SD = 0.63	11.54 SD = 0.79
Medium	M = 8.91 SD = 0.62	M = 14.45 SD = 1.09	M = 15.91 SD = 1.24
High	M = 9.94 SD = 0.613	M = 18.33 SD = 1.254	M = 24.41 SD = 1.442

We made a comparison of nine conditions in accommodation session keeping the distance as constant and varying the clutter.

For the *short-distance task*, there were significant differences in task times for low-, medium-, and high-clutter conditions ($F(1.777, 88.87) = 4.935, p = 0.012$). Pairwise comparisons using Bonferonni correction showed that the time taken to complete the task for high-clutter condition is significantly higher than the low-clutter condition ($p = 0.019$).

For *medium-distance task*, there were significant differences in task time for low-, medium-, and high- clutter conditions ($F(1.888, 94.388) = 37.584, p < 0.001$). Pairwise comparisons showed that the time taken to complete the medium-distance task for high-clutter condition is significantly higher than low-clutter ($p < 0.001$) and medium-clutter conditions ($p = 0.002$). In addition, the time taken to complete medium-distance task in medium-clutter condition is significantly higher than low-clutter condition $p < 0.001$.

For *long-distance task*, there were significant differences in task time for low-, medium-, and high-clutter conditions ($F(1.537, 76.826) = 15.002, p < 0.001$). Pairwise comparisons showed that the time taken to complete the long-distance task for high-clutter condition is significantly higher than low-clutter ($p < 0.001$) and medium-clutter conditions ($p < 0.001$). In addition, the time taken to complete medium-distance task in long-distance condition is significantly higher than low-clutter condition $p < 0.001$.

Locomotion Change

We compared the number of travel mode changes across conditions to understand the relationship between locomotion changes to changes in target distance and clutter. The mean and standard deviation values of the number of travel mode changes in each condition are listed in Table 6.10.

Table 6.10: Number of travel mode changes in various conditions

Distance/Clutter	Short	Medium	Long
Low	M = 1.17 SD = 0.39	M = 2.41 SD = 0.74	M = 3.29 SD = 0.96
Medium	M = 1.82 SD = 0.57	M = 4.11 SD = 1.01	M = 5.29 SD = 1.27
High	M = 2.41 SD = 0.56	M = 2.35 SD = 0.82	M = 6.29 SD = 1.62

There was no statistical difference between travel mode switching with change in clutter (low, medium, and high) in short distance task ($F(1.782, 28.515) = 2.606, p = 0.097$), medium distance task ($F(1.76, 28.153) = 2.899, p = 0.078$), and long-distance task ($F(1.527, 24.427) = 2.509, p = 0.113$). In the condition where there was low clutter, there were no significant differences between the number of travel mode switches for short-, medium-, and long- distances ($F(1.426, 22.818) = 3.588, p = 0.058$).

In the condition of medium clutter in the VE, there was a significant difference in the number of travel mode switches between short-, medium-, and long- distances ($F(1.403, 22.454) = 6.153, p = 0.013$). Further pairwise comparisons showed that the number of travel mode switches significantly increased from short- to long-distance task ($P = 0.048$). In high-clutter condition, there was a significant difference in the number of travel mode switches between short-, medium-, and long-distance tasks ($F(1.389, 22.221) = 6.141, p = 0.014$). Further pairwise comparisons showed that the number of travel mode switches significantly increased from medium- to long-distance task ($P = 0.041$).

Different participants used different locomotion techniques in each condition in the accommodation session for variable time and distances. We analyzed the distribution of time and distance of Teleportation, TriggerWalking and Walking-in-Place for each condition. Later, we identified the most preferred technique for each condition for each participant and analyzed the data to see if there is any significant trend among participants in choosing a particular technique for each task.

Figure 6.9 shows the normalized time distribution of locomotion techniques used by the participants for all the nine conditions in accommodation session. We observe that some participants used only a single technique for all the nine conditions: P16 used Tele, and P17 used TW for all the conditions.

We found the amount of time each participant spent using the three locomotion techniques while completing the travel tasks. From the distribution data, we identified the locomotion technique each participant for the longest time in each condition in accommodation session. The first three rows in Table 6.11 shows the number of participants that used each technique for the longest time and the Chi-Square test significant values. Further pairwise comparisons showed that for medium-distance task, when there was low clutter, participants used

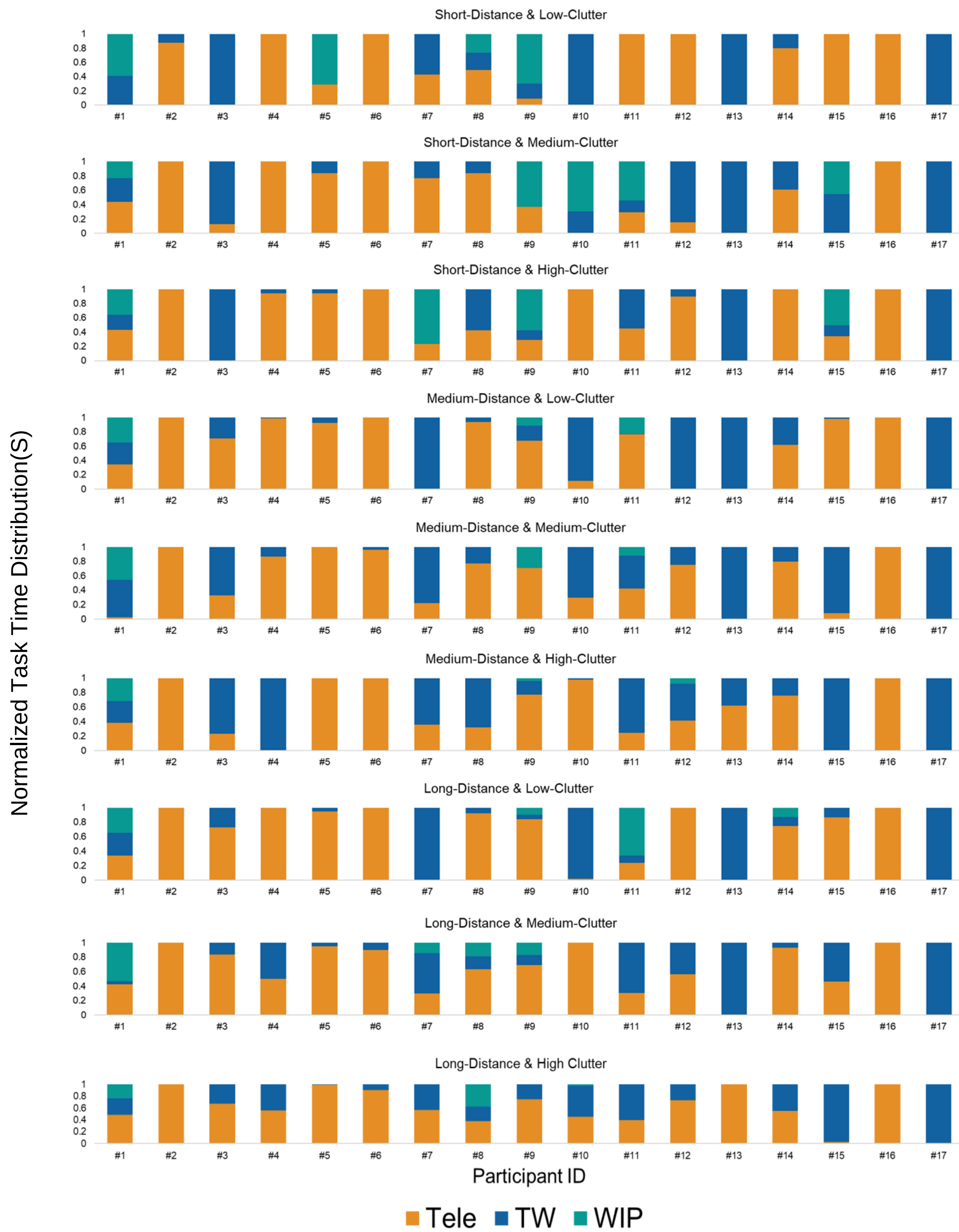


Figure 6.9: Per participant time distribution of locomotion techniques used for different conditions in Accommodation Session

Tele significantly than TW and WIP. For medium distance task with medium-clutter, participants significantly used Tele and TW over WIP.

Table 6.11: Maximum usage distribution and Chi-square scores of locomotion technique preference of participants based on time (P = Number of participants)

Cond	S-L	M-L	L-L	S-M	M-M	L-M	S-H	M-H	L-H
#P Tele	8	9	10	7	9	8	8	6	6
#P TW	6	7	5	7	7	8	6	9	9
#P WIP	3	1	2	3	1	1	3	2	2
$\chi^2(2)$	2.235	6.118	5.765	1.882	6.118	5.765	2.235	4.353	4.353
p	0.327	0.047*	0.056	0.39	0.047*	0.056	0.327	0.113	0.113

Figure 6.10 shows the distance distribution of locomotion techniques of the participants for all the nine conditions in accommodation session.

We calculated the amount of distance each participant travelled using each of the three locomotion techniques. We identified the locomotion technique that each participant used for the highest percentage of the distance in all the nine conditions. Table 6.12 shows the number of participants that used a travel mode for the maximum distance in each condition and the Chi-Square test significant values in accommodation session. For medium-distance task, when there was low-clutter, participants preferred Tele significantly more than TW and WIP. For a long-distance task with low-clutter, participants preferred Tele to TW and WIP. For a long-distance task with medium-clutter, participants significantly preferred Tele to WIP.

Table 6.12: Maximum usage distribution of locomotion technique based on distance for different conditions in accommodation session (P = Number of participants)

Cond	S-L	M-L	L-L	S-M	M-M	L-M	S-H	M-H	L-H
#P Tele	9	11	11	9	10	10	9	9	11
#P TW	5	5	4	5	7	6	5	8	5
#P WIP	3	1	2	3	0	1	3	0	1
$\chi^2(2)$	3.294	8.941	7.882	3.294	0.529	7.176	3.294	0.059	8.941
p	0.193	0.011*	0.019*	0.193	0.467	0.028*	0.193	0.808	0.11

From the video analysis, we found that the mean time taken for travel mode change in accommodation session is 0.83 seconds (SD=0.46).

At the end of the accommodation session, we collected participant's subjective response for SSQ, NASA-TLX, SUS, and IPQ presence questionnaire. The mean incremental simulator sickness score compared to the pre-experiment SSQ measure in accommodation session was 2.9 (SD = 15.64). Three participants had SSQ score of more than 20. The mean SUS score in accommodation session was 82.64 (SD = 9.64). To measure

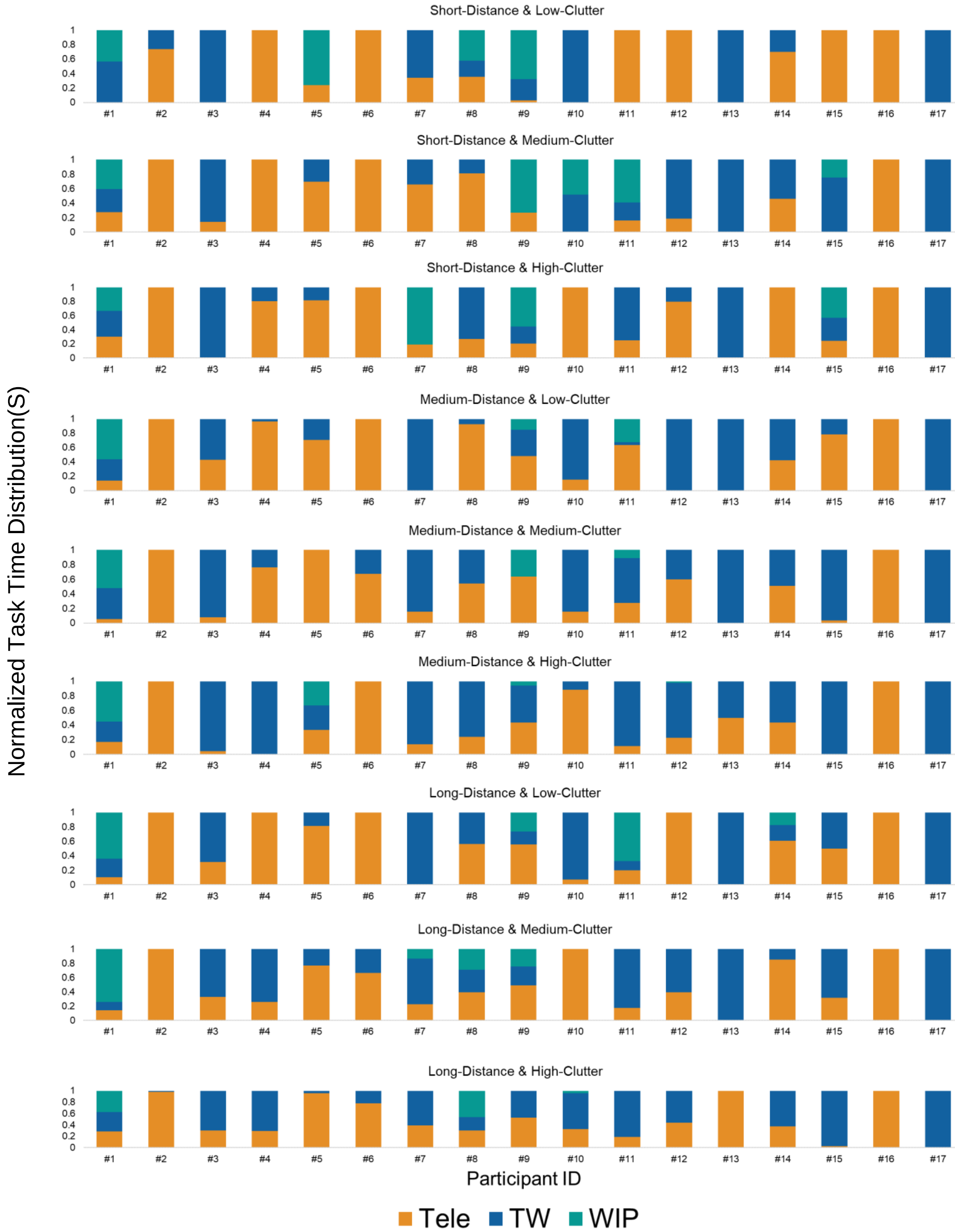


Figure 6.10: Per participant distance distribution of locomotion techniques for different conditions in Accommodation Session

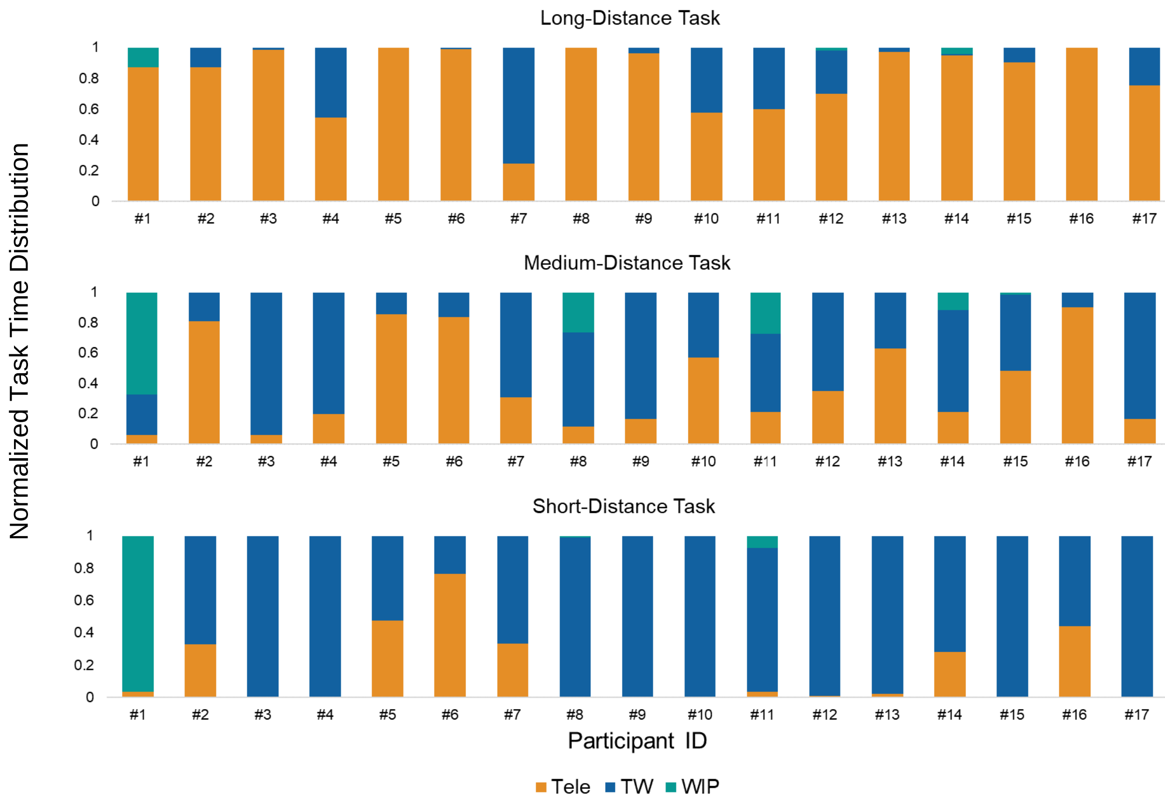


Figure 6.11: Per participant time distribution of locomotion techniques for different conditions in Testing session

the participant's subjective feeling of workload, we computed the NASA-TLX index score, and the mean was 259.88 (SD = 132.86). Using IPQ presence questionnaire, we computed the general presence (M = 5.22, SD = 0.71), spatial presence (M = 4.43, SD = 0.78), realism (M = 4.36, SD = 1.16), and involvement (M = 2.9, SD = 0.91) of participants.

Final Testing Session

In the testing session, the mean time taken (measured in seconds) to complete the long-distance task was 145.93 (SD = 34.5), medium-distance task was 131.71 (SD = 51.65), and short-distance task was 116.79 (SD = 38.27). The mean score (number of vases collected, maximum score = 12) in the medium-distance task was 11.55 (SD = 0.59). The number of wall collisions in the medium-distance task was 0.83 (SD = 0.95). The mean negative score (number of red cylinders touched or collided) was 1.05 (SD = 1.87).

To understand the participant preference, we found the locomotion techniques used for highest % of time in long-, medium-, and short-distance tasks. Figure 6.11 shows the time distribution of locomotion techniques used by participants for long-, medium-, and short-distance task in the testing session.

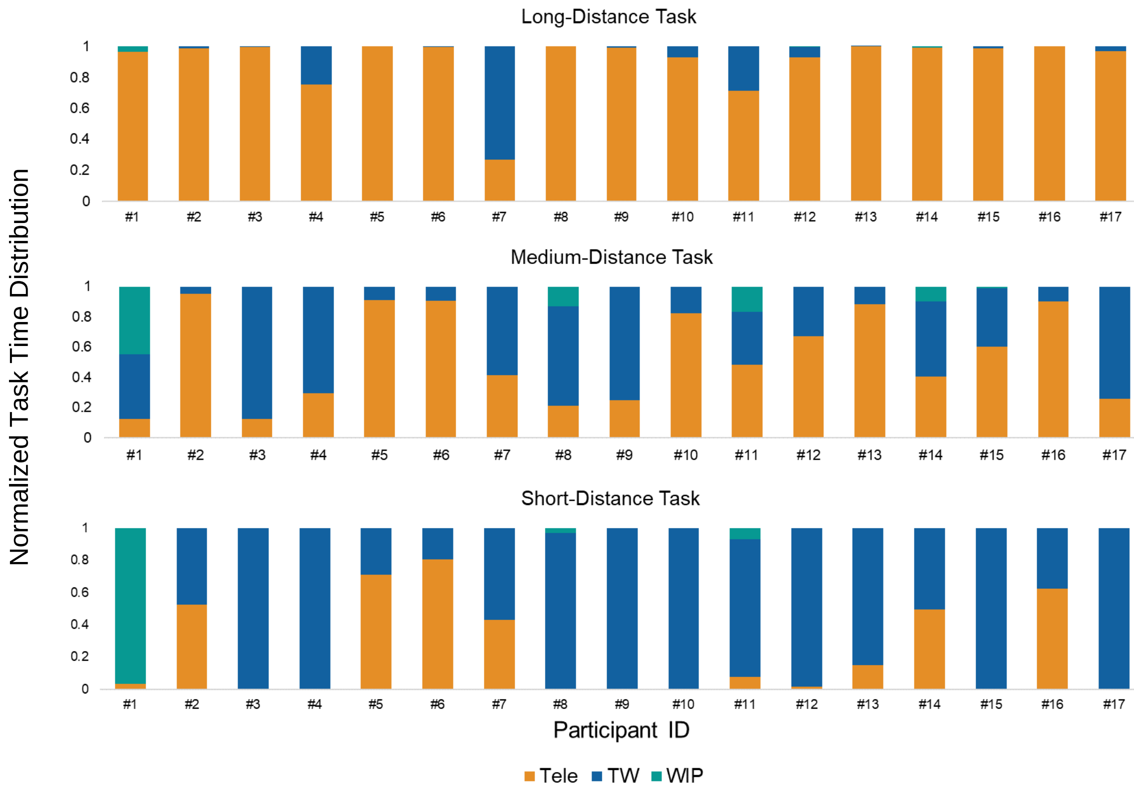


Figure 6.12: Per participant distance distribution of locomotion techniques for different conditions in testing session

Table 6.13 shows the participants locomotion usage based on time distribution for long-, medium-, and short-distance tasks in testing session based on time and the Chi-Square test significant values in the final testing session.

Table 6.13: Distribution of Participants most used locomotion technique based on time for long-, medium-, and short-distance tasks in testing session

Tech	L	M	S
#P Tele	16	7	1
#P TW	1	8	15
#P WIP	0	2	1
$\chi^2(2)$	13.235	3.647	23.059
p	<0.001*	0.161	<0.001*

Chi-square tests showed that there was a significant difference in the usage of each locomotion technique for long- and short-distance tasks. For the long-distance task, participants mostly used Tele compared to TW and WIP. For short-distance task, participants significantly used compared to Tele to WIP.

To further analyze the locomotion technique participants used most, we identified the locomotion technique, each participant used most of the distance for long-, medium-, and short-distance task. Figure 6.12 shows the distance distribution of locomotion techniques used by each participant for long-, medium-, and short-distance task in the testing session.

Table 6.14 shows the number of participants that used each locomotion technique for the maximum distance for long-, medium-, and short-distance tasks based on distance. Chi-square tests showed that there was significant difference in usage of each locomotion technique for long-, medium-, and short-distance tasks. Further pairwise comparisons showed that, for long-distance task, participants used Tele more than TW and WIP. For medium- and short- distance tasks participants used TW more than Tele and WIP. Figure 6.13 shows the travel mode changes for different conditions.

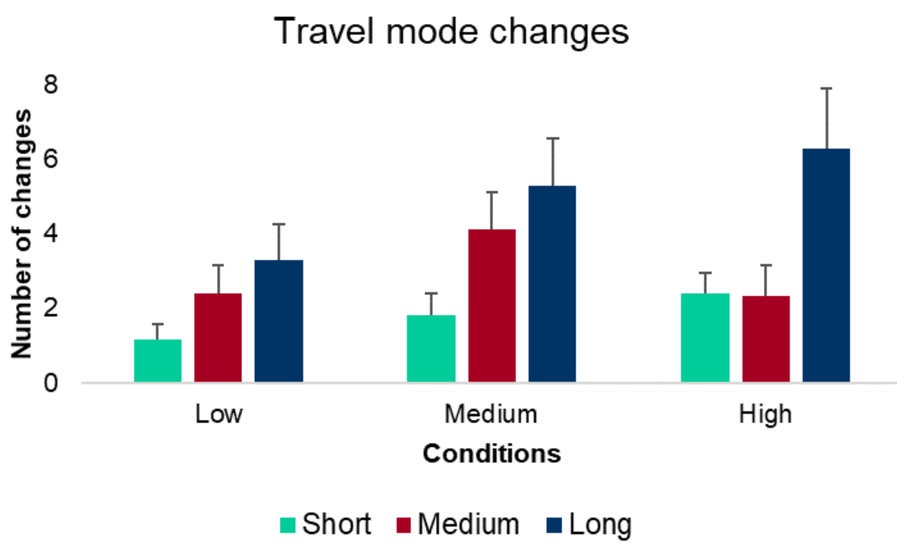


Figure 6.13: Travel mode changes

Table 6.14: Participants preferred locomotion technique based on distance in testing session

Tech	L	M	S
#P Tele	16	9	4
#P TW	1	7	12
#P WIP	0	1	1
$\chi^2(2)$	13.235	6.118	11.412
p	0.001*	0.042*	0.003*

The mean and standard deviation values of the number of travel mode changes in the final testing session is listed in Table 6.15. There was a significant difference between the number of travel mode switches between

Table 6.15: Travel mode changes in final testing session

Cond	Long	Medium	Short
Mean	4.47	12.44	4.11
SD	1.19	2.32	1.32

long-, medium-, and short distance tasks ($F(1.401, 22.409) = 8.527, p = 0.004$). Pairwise comparisons showed that participants switched significantly more in the medium-distance task than long-distance ($p = 0.001$) and short-distance ($p = 0.034$) tasks.

At the end of the testing session, we collected participant's subjective response for SSQ, NASA-TLX, SUS, and IPQ presence questionnaire. The mean incremental simulator sickness score in testing session was 9.97 (SD = 12.95). Three participants had SSQ score of more than 20. The mean SUS score in testing session was 78.75 (SD = 14.9). To measure the participant's subjective feeling of workload, we computed the NASA-TLX index score, and the mean was 283.5 (SD = 88.76). Using IPQ presence questionnaire, we computed the general presence (M = 4.66, SD = 1.05), spatial presence (M = 4.18, SD = 0.89), realism (M = 4.19, SD = 1.09), and involvement (M = 2.76, SD = 0.91) of participants.

Post-experiment Questionnaire

At the end of the testing session / Day 2, participants answered the questionnaire on preferred locomotion techniques. Nine participants preferred Tele, and eight participants preferred TW. Participants who preferred Tele described the locomotion technique as fast, easy to learn to require less physical movement. Participants who preferred TW described it as the locomotion technique having control over movement, easy to learn, less sickness-inducing, and the best option for precise movement.

After completing the post-experiment questionnaire, participants were asked about their strategy in choosing/switching between locomotion techniques. Some of the answers were:

- I used Teleportation to go long distances faster. With Tele, I felt I had better control, and WIP was used only to maneuver around objects some times.
- I was concentrating on optimizing effort, hence Tele for long distances, and TW when there were obstacles in the environment.
- Even though I felt Tele is easy, I used TriggerWalking to go around things, and I felt I did not have to use WIP to complete the tasks.

For the interview questionnaire on having a choice to choose locomotion technique, all the participants preferred having a choice. Sixteen out of seventeen reported switching between techniques was natural, and they did not have to think much before switching techniques. One participant reported that if a technique was not used for a long time and if she had to use it again, she had to think a bit about how the locomotion technique works. In this case, the participant was using Tele for long- and medium-distance task in the testing session. For the short-distance task, she stopped to think about how TW works and then used TW to complete the task.

6.4.3 Path Visualizations

Path visualizations helped us understand some of the behaviours of participants. We used MATLAB to plot the head tracker data of the participant on the 2D projection of the environment in the testing session.

Figure 6.14 shows a simple visualization of the paths taken by two participants to complete the long-distance task in final testing session. A is the starting position and B is the end position of the long-distance task. The blue scatter points represent Teleportation, red scatter points represent TriggerWalking, and green scatter points represent Walking-in-Place. In the first path, we can see the travel mode switch between Tele to TW near bends. In the second path, the participant started the task with WIP (shown in green), then used Tele and switched back to WIP while nearing the end point and did not use TW in long-distance task.

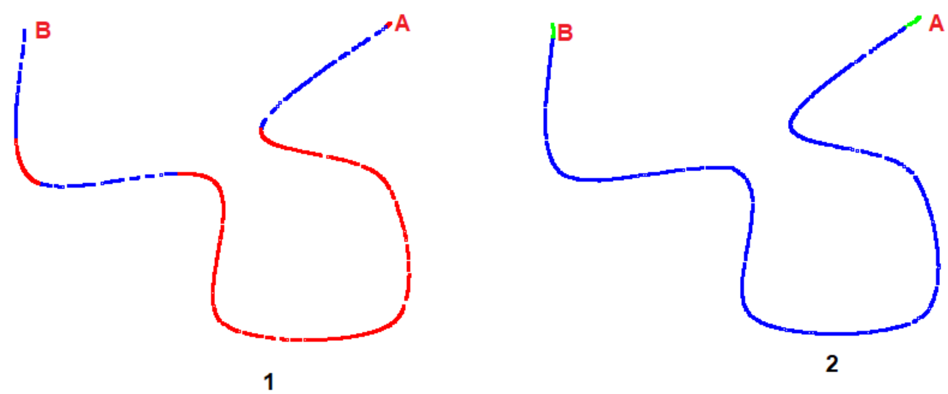


Figure 6.14: Path visualization of long-distance task (1000m) of two participant #7 and participant #9. The blue points represent Tele, red represent TW, and green represent WIP.

Figure 6.15 shows path taken by four different participants. A and B denotes starting and stopping positions of medium-distance task. In the first path, we can observe that TW (red points) was used to travel most of the distance, however, when there is a very clear line of sight, Tele (blue points) was used. In path 2, Tele was used to travel most of the distance except near some of the turns. In paths 3 and 4, we can see that when there is a clear line of sight, Tele was used and when there are turns, bends or near the vases, TW or WIP was used.

In the short-distance task, participants used TW more than Tele or WIP. In path 1, we see that participant used TW more than WIP and in path 2 TW is used to complete the short-distance task. In path 3, the participant used mostly WIP to complete the short-distance task.

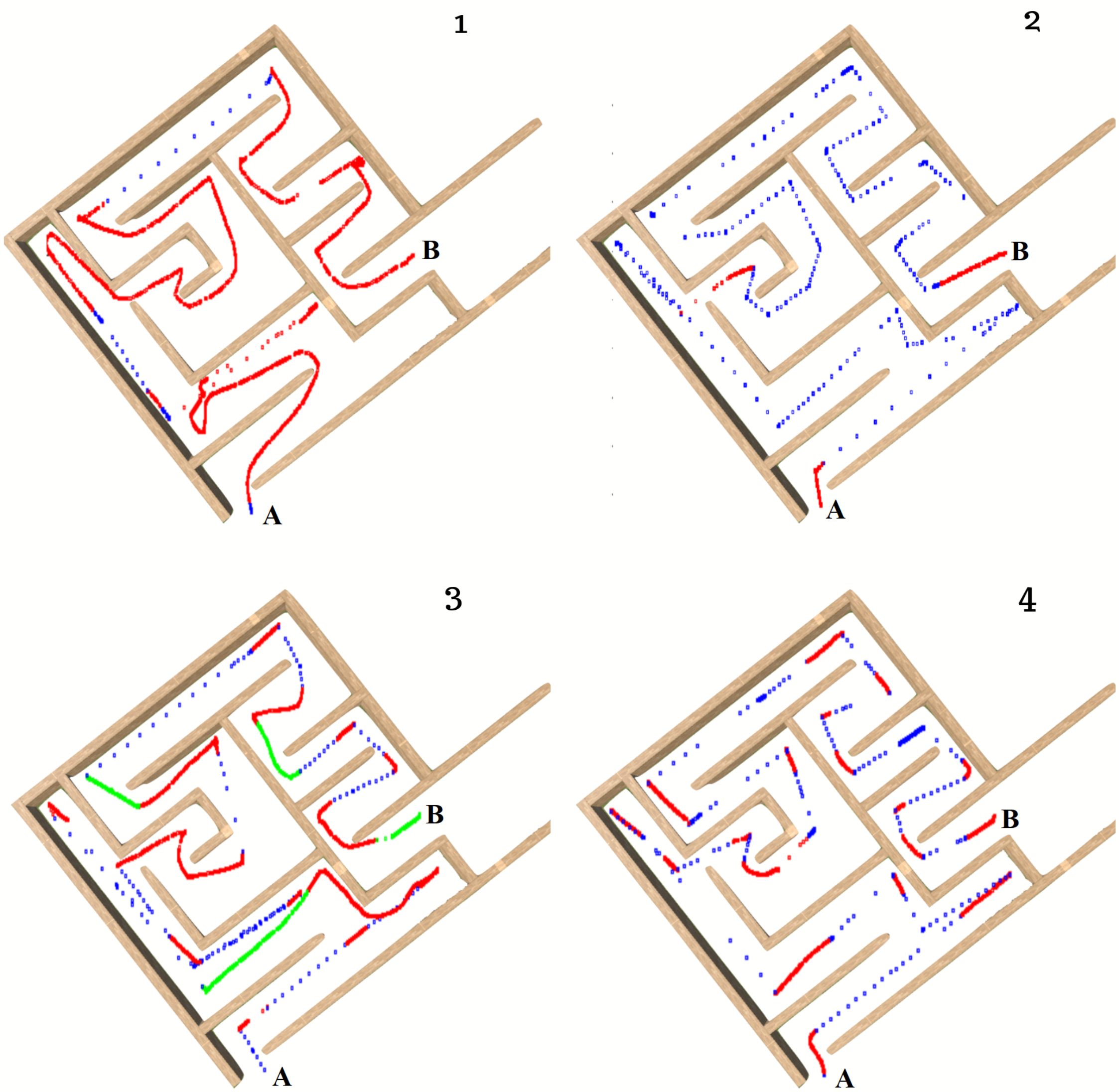


Figure 6.15: Path visualization of four participant #3, participant #7, participant #8 and participant 15 for medium-distance task. Blue dots denotes Tele, Red dots denote TW and Green dots denote WIP.

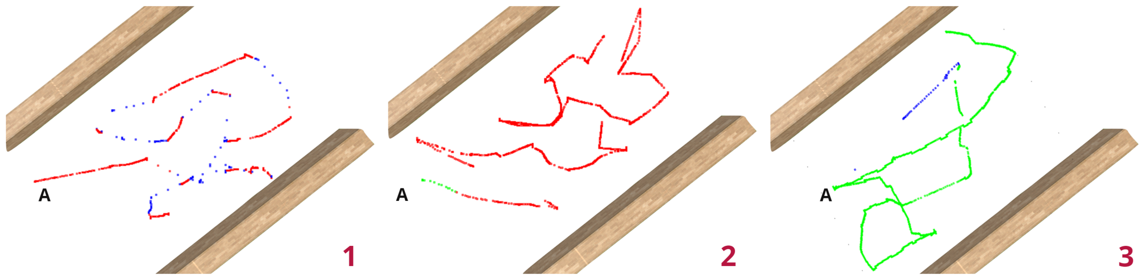


Figure 6.16: Path visualization of short-distance task for participant #2, participant #3 and participant #1. A represents the starting position of the short-distance task

6.5 Discussion

This user study investigates the behavior of participants in choosing/switching multiple travel modes in complex VEs when they are trained in each travel technique to proficiency.

6.5.1 Training Session/Day 1

In the training session, there was a significant decrease in mean task time from trial 1 to trial 10 for difficulty level 1 for accuracy training for all three locomotion techniques. We attribute the decrease in mean task time to the increase in proficiency of participants over ten trials. In the accuracy training, participants were asked to reach the red target and to avoid obstacles, and the mean collisions with obstacles were negligible (< 1). One reason for negligible collisions could be that participants learned to avoid obstacles and simultaneously to reach the target faster. In the speed training, there was no significant improvement in mean task time over ten trials in three levels showing a ceiling effect. One reason could be that participants have already reached an optimal level of expertise in difficulty level 1 of accuracy training and that there was no significant deviation in task time in speed training. Participant's subjective self-proficiency rating score showed that participants were more confident that they were proficient in Teleportation compared to Walking-in-Place.

6.5.2 Accommodation Session/Day 2

There was a significant increase in time taken to complete the tasks with an increase in distance when clutter is assumed as constant irrespective of travel mode participant chose. In TW and WIP implementation, the time to reach the target primarily depends on distance, since the participant has to travel the distance. In the case of Teleportation, the participant had to identify the target and un-press the touchpad to instantaneously jump to the target destination. The time taken to teleport in this case is irrespective of the distance. Hence, theoretically, it takes equal time to complete the task with different distances (long-, medium-, and short-) using Tele when the participant has a clear line of sight to the target.

Even though Teleportation instantaneously transported participants to the target location, participants took longer times as the target distance increased. However, the mean task times increased with increase in distance. Our video analysis of participants gameplay showed that participants increased the number of teleports as the distance increased even though they could reach the longer distance in a single teleport to the target location. The mean task time also increased with an increase in clutter. The increase in time with an increase in clutter supports the findings of previous studies [132, 5]. It was also interesting to observe that, even in the environment with high clutter, the mean number of collisions (< 1) was small with participants not colliding with other objects in VE. One reason could be that participants cared more about not touching the objects rather than reaching the target as fast as possible.

6.5.3 Testing Session/Day 2

In the long-distance task, based on the results published in previous user studies [24, 11, 32, 36], we expected participants to use Teleportation since it was the most efficient technique to travel faster and farther. In the testing session, we observed that six participants initially started travelling using TW, and two participants started travelling using WIP and all of the participants changed to Tele. Participants showed the ability to switch to the more efficient locomotion technique in the long-distance scenario. One participant, as seen in path 1 of Figure 6.15 used TW first for maximum percentage of the distance and switched to Tele later in the task. When asked for a reason behind using TW in the long-distance task, a participant commented that it was her first time to use VR and she wanted to look around and enjoy the scenario rather than jump to target soon.

In the medium-distance task, we observed that many participants tend to use Tele for areas with a straight and clear line of sight to the vase. When the participants reached near the vase, they used TW or WIP to go near the vase to collect it. Participants travelled longer distances with a clear line of sight using Tele and travelled smaller distances to pick up a vase or go around the bends using TW and WIP.

We chose travel techniques for M-Travel mode that were shown to have a lower incidence of simulator sickness and high usability (SUS) in previous user studies [158, 118, 87]. The effect of our choosing these travel techniques was reflected in the mean SSQ and SUS scores. The mean SSQ scores after the accommodation session and the final testing session were negligible or minimal (< 10) [146]. The mean SUS scores showed that the usability of M-Travel mode is good(based on Kennedy interpretation of scores) [67]. Another reason for the high level of comfort and usability could be the control given to participants to choose whichever travel mode they felt fit for the task. Previous research by Turner et al. [162] shows that the user's control over movement contributes to the comfort of the users.

The interview responses showed that all the participants followed a very similar strategy in using different travel modes: Participants chose Tele when they felt a need for travelling faster or longer and used TW or WIP when they needed more control. In testing session/Day 2, we informed the participants that the three travel techniques that they learned in practice session were available for them to use to complete the tasks. We made sure that we did not say they had to use all the techniques since we wanted to avoid any bias. We observed that all the participants switched between at least two techniques. Ten participants never used WIP, and when asked about it at the end of the session, six participants said that they never felt the need to use WIP to complete the tasks since they felt Tele and TW helped them complete the tasks with ease. Four participants reported that WIP was strenuous compared to Tele and TW, and hence they avoided WIP. The less frequent use of WIP suggests that even though we chose to include three travel techniques based on our hypothesis and the findings from previous studies, having Tele and TW would have been enough. One participant commented that after using a single locomotion technique for a long time, she needed some time to think about how the other travel techniques work in order to switch between the techniques. The rest of the participants (16 out of 17) reported that it was effortless to switch travel modes, and they did not have to think much about how techniques work before switching. Training participants to proficiency could be one of the reasons for ease in switching travel modes. All of the participants answered that they preferred using M-Travel mode to a single travel mode confirming our hypothesis.

6.5.4 Limitations

To analyze our data, we assumed that if participants spent a highest percentage of a total time or distance using a technique, that is the preferred technique of the user. This does not have to be true in all cases since the participants might prefer techniques based on a different criteria, e.g., some participants might such as using WIP for fun. Using Tele, users can travel longer distances in less time. Hence, even if a participant used Teleportation for longer distances, and took more time to travel small distances using TW and WIP, that does not mean participant preferred TW or WIP. The relationship between the task and travel mode was more complicated than comparing time and distance distributions. While computing the travel mode change time, we could only count the time between when the participant stopped using a travel mode and then started used another travel mode. We assumed that the time we computed was the time taken for a participant to switch between modes. However, this might not be the case for every participant. The participant could have stopped to look at the surroundings or plan the path. It was impossible for us to objectively find the intent of the participant in stopping.

6.6 Conclusion

We conducted a user study to understand participants preference in choosing/switching travel techniques in complex VEs. The study consisted of a training session before the testing session that was conducted in consecutive days. Participants were trained to proficiency to make sure that they were well trained in each technique. The results showed that participants changed the travel mode based on variation in distance and clutter level. Participants significantly used Teleportation when there was low-clutter (clear line of sight) and when they had to travel longer distances faster. Participants chose TriggerWalking when they needed more control of movement to maneuver around objects or travel short distances. We conclude from the mean travel mode change time and interview that it is rather easy to change/switch travel modes. In conclusion, M-Travel mode with a suite of travel techniques carefully selected based on the VE and the travel tasks can be a better solution for locomotion in a complex VE.

Chapter 7

Conclusion

Locomotion in VR is still an open problem with half solutions. This dissertation investigates comfortable and usable locomotion techniques in VR and presents Multi-Travel mode (M-Travel mode) that gives users, ability to choose/switch locomotion technique based on the task, VE, and user's preference. This dissertation confirms the thesis: *"TriggerWalking and Multi-Travel mode are two novel locomotion interfaces that are both comfortable and usable"*.
Our main research contributions are:

7.1 Key Contributions

- *TriggerWalking and its evaluation*
  In Chapter 2, we explored the characteristics of an ideal locomotion technique that is comfortable and has high usability. In chapter 3, we presented the implementation of a novel bio-mechanically inspired locomotion technique: TriggerWalking. Firstly, we included the attributes of a comfortable and usable locomotion technique, and implemented them in our novel locomotion technique. The results from the user study on TriggerWalking showed that it was comfortable and easy to learn. We evaluated TriggerWalking with the existing locomotion techniques Joystick, Walking in Place, and Teleportation. The results showed that TriggerWalking had least Simulator Sickness Scores, had the least mental and physical demand, and most preferred locomotion technique. Finally, we evaluated TriggerWalking with Game-controller based locomotion techniques which were Joystick and SpeedPad. The results confirmed that TriggerWalking is the most comfortable and usable compared to the other two conditions. Even though TriggerWalking is suitable for small to medium distance tasks, it is not suitable for tasks that require hand-held controllers. TriggerWalking is also not suitable for long-distance tasks because of finger fatigue on prolonged use.

- *Multi-Travel mode*
  A single locomotion technique cannot address the requirements of different Virtual Environments and tasks. As a solution, we introduced the concept of a M-Travel mode that has a suite of locomotion techniques that can be used based on VE, travel task, personal preference, and input devices. Our hypothesis was ”Users prefer M-Travel mode over using single locomotion technique in complex VEs”.
- *Locomotion Usability Test Environment (LUTE)*
  To date, there is no standard testbed Environment that can systematically evaluate locomotion techniques for complex VEs of different sizes that accommodate different travel tasks. In Chapter 4, we implemented LUTE, a software framework that automatically generates VEs of different sizes and path lengths based on the requirements of the researcher.
- *M-Travel mode with Pre-selected locomotion techniques*
  We implemented two versions of M-Travel mode: 1. M-Travel mode with pre-selected locomotion techniques, 2. M-Travel mode with locomotion choice. In Chapter 5, we evaluated M-Travel mode (Pre-selected) for comfort, usability, and preference compared to using Joystick, Teleportation, and (multiple locomotion techniques). We evaluated M-Travel mode (Pre-selected) for two posture conditions: sitting and standing. We found that TPad induced more cybersickness than Tele. We found no evidence that participants prefer M-Travel mode (Pre-selected) to single locomotion techniques.
- *M-Travel mode with User-selected locomotion techniques*
  In Chapter 6, we report on a user study to understand participants preference in choosing/switching locomotion techniques in complex VEs. The user study had separate training and testing sessions. The results showed that participants changed the locomotion techniques based on variation in distance and clutter level. From the interviews and remarks for the participants, we found that participants preferred having a choice in selecting a locomotion technique, and it was easy and intuitive to switch between different pre-trained locomotion techniques.

The findings from this dissertation do not state that everyone has to use multiple locomotion techniques in VR applications. It supports the argument that the users or consumers of VR should have an option to choose an alternative locomotion technique if the technique they are using is not the right fit or make them uncomfortable. Having single locomotion that might cause uncomfortable side effects leads to less adoption and reduction in the use of the application. This dissertation contributes by introducing the concept of M-Travel mode, a better solution for locomotion in complex VE.

A limitation of this dissertation is sample sizes in the user studies. The sample sizes are selected based on the number of conditions in the user study and the sample sizes in similar user studies. Performing a power analysis prior to the user study to determine the sample size is a preferred approach. Collecting data from more participants in the user studies leads to more generalised results instead of being biased by different factors (gender, age and level of experience).

The next step would be to evaluate different locomotion techniques using LUTE for different tasks and make a database on the suitability of a travel technique for a VR application based on the VE, task, display devices, and input devices. Using this database, we can develop a Unity/Unreal plugin that can automatically enable the most suitable locomotion technique for each application.

To design the standard locomotion testbed LUTE, we identified attributes listed in Chapter 4. We implemented some of the main attributes necessary for the user studies. In future, we can implement other attributes such as dynamic obstacles/distractors, dynamic weather etc. We can also include a way to automatically generate the questionnaire needed for user study and update the LUTE user interface accordingly.

To evaluate M-Travel mode (User-selected), we trained participants to proficiency based on the score threshold we set. There is no formal framework for training participants in each locomotion technique or to measure their proficiency. In future, we can develop a set of simple VEs, tasks, and evaluation strategies to train the participants in locomotion techniques before using the VR applications.

Users chose locomotion technique based on target distance and clutter in M-Travel mode (choice). We can develop an application that does a real-time scene analysis of the view of the user in VR and suggests the locomotion technique they can use.

This dissertation aims to address comfort and usability issues in current locomotion techniques. We introduced Multi-mode travel to give users the freedom to choose a comfortable and efficient technique to use in VR applications. We hope that the further research and evaluation into M-Travel mode makes it more flexible and encourages the game designers to include it in future games.

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Chapter 8

Appendix

This chapter contains the information sheets, consent forms and questionnaires used for all the user studies.

Telephone: +64 3 364 2349
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20.03.2017

Participant Information Sheet

for

Bio-mechanically inspired locomotion user interface for pseudo-realistic virtual walking

I am Bhuvaneswari Sarupuri, a PhD student at the HIT Lab NZ and I am conducting this research as part of my doctoral studies. I am interested in exploring ways how humans can walk in virtual environments. In this study I am collecting data to improve and evaluate a finger-based walking technique.

The following researchers will help me with this study: Professor Rob Lindeman (my supervisor), Professor Frank Steinicke (a visiting academic from Hamburg, Germany), Yuanjie Wu (a PhD student at the HIT Lab) and Simon Hoermann (a researcher at the HIT Lab).

If you choose to take part in this study, your involvement in this project require you to wear a head mounted display (HTC Vive) and you will also be required to do one of the following:

a) Walk several times on a predefined path in an outdoor virtual environment and then complete a short questionnaire on demographics (e.g. height, age, vision, leg preference). The estimated time to complete all tasks is less than 15 minutes. You will be compensated for your time with a chocolate bar.
b) Walk in an outdoor virtual environment towards a number of predefined locations, using different finger-based walking techniques (gestures). You will be asked to complete several questionnaires, before, during, and after the experiment. The estimated total time is 60-90 minutes. You will be compensated for your time with a 20$ gift voucher.
c) Walk in a closed virtual environment (interior of a house) and virtually carrying out activities of daily living. You will be asked to complete several questionnaires, before, during and after the experiment. The estimated total time is 60-90 minutes. You will be compensated for your time with a 20$ gift voucher.

During your time in the virtual environment, your movements will be recorded e.g. how you move or how your head is moving during walking. However, no identifiable information will be collected at any point in this study (e.g. name, address).

In the performance of the tasks and application of the procedures there is a risk of dizziness (also known as cyber-sickness) due to the use of the head mounted display. Many factors that can cause cyber-sickness have been mitigated through our current hardware system, however, there is still a chance that you might experience some of the symptoms. You are allowed to stop the experiment at any time or extend the period between sessions to as long as you need. We will also offer a couch where you can relax until the symptoms have faded.

Your participation is voluntary and you have the right to withdraw at any stage during the experiment without penalty. You may ask for your raw data to be returned to you or destroyed at any point during the experiment. If you withdraw, no data will be stored. However, once the experiment is completed, it will not be possible to remove your data due to its anonymous storage.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public. To ensure anonymity and confidentiality, all the data is stored securely and only the researchers mentioned above will have access to it. However, I might also share parts of the raw anonymized data with other researchers if there is a need to do so. The data will be kept securely stored for a minimum period of 10 years on storage systems within the University of Canterbury, and securely destroyed after that.

The outcomes of this research may be published in scientific outlets such as conferences and journals as well as part of my PhD thesis. A thesis is a public document and will be available through the UC Library. Major dissemination of this research will be announced on the Facebook page of the HIT Lab NZ (www.facebook.com/HITLabN) where a link to the published documents will be provided.

The project is being carried out under the supervision of Professor Rob Lindeman, who can be contacted at gogo@hitlabnz.org and +64 3 364 2403. He will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and return it before commencing the experiment.

This sheet is for you to keep if you wish

Telephone: +64 3 364 2349
Email: bhuvan.sarupuri@pg.canterbury.ac.nz
20.03.2017

Consent Form

for

Bio-mechanically inspired locomotion user interface for pseudo-realistic virtual walking

- ☐ I have been given a full explanation of this project and have had the opportunity to ask questions.
- ☐ I understand what is required of me if I agree to take part in the research.
- ☐ I understand that participation is voluntary and that I may withdraw at any time without penalty. Withdrawal of participation will also include the withdrawal of any information I have provided should this remain practically achievable.
- ☐ I understand that any information or opinions I provide will be kept confidential to the researcher Bhuvaneswari Sarupuri, Rob Lindeman, Frank Steinicke, Yuanjie Wu and Simon Hoermann, and that any published or reported results will not identify the participants. I understand that parts of the raw anonymized data could be shared with other researchers if there is a need to do so.
- ☐ I understand that results of this research are intended to be published as part of a PhD thesis, which is a public document available through the UC Library.
- ☐ I understand that all data collected for the study will be kept in locked secure facilities in a password protected and encrypted electronic form and will be destroyed after no less than ten years.
- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I understand that I can contact the researcher Bhuvaneswari Sarupuri (bhuvan.sarupuri@pg.canterbury.ac.nz, +64 3 364 2349) or supervisor Professor Rob Lindeman (gogo@hitlabnz.org, +64 3 364 2403) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
- ☐ I understand that I can access the Facebook webpage of the HIT Lab www.facebook.com/HITLabN to find information about disseminations and summaries of the outcomes of this research once they become available.
- ☐ By signing below, I agree to participate in this research project.

Name:____________________________ Signed:__________________________ Date:________________

Please complete and return this consent sheet to the researcher conducting the experiment before commencing the study

Telephone: +64 3 3642349
Email: bhuvan.sarupuri@pg.canterbury.ac.nz
29.5.2018

Participant Information Sheet
for
Evaluation of locomotion techniques for travel in the virtual environment

I am Bhuvaneswari Sarupuri, a Ph.D. student at the HIT Lab NZ and I am conducting this research as part of my doctoral studies. I am interested in evaluating locomotion techniques for travel in Virtual Environment. In this study, I am collecting data to improve and evaluate finger-based walking techniques. The following researchers will help me with this study: Professor Rob Lindeman (my supervisor), Simon Hoermann , (Associate supervisor), Mary C Whitton (A researcher in UNC Chapel Hill), Sam Selwyn (a PhD student at UC) and Sungchul Jung (a Postdoc at HITLabNZ).

If you choose to take part in this study, your involvement in this project requires you to wear a head mounted display (HTC Vive) and you will also be required to do the following:

a. Walk in an outdoor and indoor virtual environment towards a number of predefined locations, using different finger-based walking techniques (gestures) and collect objects highlighted.
b. You will be asked to complete several questionnaires, before, during, and after the experiment.

The estimated total time is 60-90 minutes. You will be compensated for your time with a 20$ gift voucher. During your time in the virtual environment, your movements will be recorded e.g. how you move or how your head is moving during walking. However, no identifiable information will be collected at any point in this study (e.g. name, address).

In the performance of the tasks and application of the procedures, there is a risk of dizziness (also known as cyber-sickness) due to the use of the head-mounted display. Many factors that can cause cyber-sickness have been mitigated through our current hardware system, however, there is still a chance that you might experience some of the symptoms. You are allowed to stop the experiment at any time or extend the period between sessions to as long as you need. We will also offer a couch where you can relax until the symptoms have faded.

Participation is voluntary and you have the right to withdraw at any stage without penalty. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, I will remove information relating to you. However, once analysis of raw data starts on 03/07/2018, it will become increasingly difficult to remove the influence of your data on the results.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality, all the data is stored securely and only the researchers mentioned above will have access to it. However, I might also share parts of the raw anonymized data with other researchers if there is a need to do so. The data will be kept securely stored for a minimum period of 10 years on storage systems within the University of Canterbury, and securely destroyed after that.

The outcomes of this research may be published in scientific outlets such as conferences and journals as well as part of my Ph.D. thesis. A thesis is a public document and will be available through the UC Library. Major dissemination of this research will be announced on the Facebook page of the HIT Lab NZ (www.facebook.com/HITLabNZ) where a link to the published documents will be provided.

Bhuvaneswari sarupuri

Please indicate to the researcher on the consent form if you would like to receive a copy of the summary of results of the project.

The project is being carried out as a requirement for a Ph.D. degree in Human Interface Technology by Bhuvaneswari Sarupuri under the supervision of Professor Rob Lindeman (gogo@hitlabnz.org) and Dr. Simon Hoermann (simon.hoermann@canterbury.ac.nz). They will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and return it before commencing the experiment.

This sheet is for you to keep if you wish

Bhuvaneswari sarupuri

Telephone: +64 3 3642349
Email: bhuvan.sarupuri@pg.canterbury.ac.nz
29.5.2018

Consent Form
for
Evaluation of locomotion techniques for travel in virtual environment

☐ I have been given a full explanation of this project and have had the opportunity to ask questions.

☐ I understand what is required of me if I agree to take part in the research.

☐ I understand that participation is voluntary and I may withdraw at any time without penalty. Withdrawal of participation will also include the withdrawal of any information I have provided should this remain practically achievable.

☐ I understand that any information or opinions I provide will be kept confidential to the researchers Bhuvaneswari Sarupuri, Rob Lindeman, Simon Hoermann, Mary C Whitton, Sam Selwyn and Sungchul Jung and that any published or reported results will not identify the participants.

☐ I understand that a thesis is a public document and will be available through the UC Library.

☐ I understand that all data collected for the study will be kept in locked and secure facilities in password protected electronic form and will be destroyed after no less than 10 years.

☐ I understand the risks associated with taking part and how they will be managed.

☐ I understand that I can contact the researcher Bhuvaneswari Sarupuri (bhuvan.sarupuri@pg.canterbury.ac.nz, +64 3 364 2349) or supervisors Professor Rob Lindeman (gogo@hitlabnz.org, +64 3 364 2403) and Dr. Simon Hoermann (simon.hoermann@canterbury.ac.nz) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)

☐ I would like a summary of the results of the project.

☐ By signing below, I agree to participate in this research project.

Name:_____________________________Signed:___________________________Date:________________

Email address *(for report of findings, if applicable)*:____

Please complete and return this consent sheet to the researcher conducting the experiment before commencing the study

Bhuvaneswari sarupuri

Department: HIT Lab NZ

Telephone: +64 3 369 0219
Email: bhuvan.sarupuri@pg.canterbury.ac.nz
02/05/2019
HEC Ref: [Enter when approval given for your study]

Comfortable and usable locomotion techniques in VR

Information Sheet for participant

I am Bhuvaneswari Sarupuri, a Ph.D. student at the HIT Lab NZ and I am conducting this research as part of my doctoral studies. I am interested in evaluating comfortable and usable locomotion techniques for travel in Virtual Environment. In this study, I am collecting data to improve and evaluate finger-based walking techniques in virtual reality. Your participation will help us evaluate the effectiveness of our system and provide vital information about the suitability of the system. We will fit you with a physiology sensor to measure your heart rate and other vital signs. We will also record your game play and record interview audio for later analysis.

The following researchers will help me with this study: Professor Rob Lindeman (my supervisor), Sungchul Jung (Co-supervisor), Simon Hoermann (Associate supervisor) and Mary C Whitton (A researcher in UNC Chapel Hill).

If you choose to take part in this study, your involvement in this project requires you to wear a head mounted display (HTC Vive), attend two experiment sessions and you will also be required to do the following:

a. In session 1, travel in outdoor environment to reach the target location using three locomotion techniques.
b. In session 2, travel in an indoor and outdoor environment to reach the target location using three locomotion techniques.
c. You will be asked to complete several questionnaires, before and after the experiment.

The estimated total time is 45-60 minutes. You will be compensated for your time with a 10$ gift voucher. During your time in the virtual environment, your movements will be recorded e.g. how you move or how your head is moving during walking. However, no identifiable information will be collected at any point in this study (e.g. name, address).

In the performance of the tasks and application of the procedures, there is a risk of dizziness (also known as cyber-sickness) due to the use of the head-mounted display. Many factors that can cause cyber-sickness have been mitigated through our current hardware system, however, there is still a chance that you might experience some of the symptoms. You are allowed to stop the experiment at any time or extend the period between sessions to as long as you need. We will also offer a couch where you can relax until the symptoms have faded.

Participation is voluntary and you have the right to withdraw at any stage without penalty. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, I will remove information relating to you. However, once analysis of raw data starts on 27/05/2019, it will become increasingly difficult to remove the influence of your data on the results.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality, all the data is stored securely and only the researchers mentioned above will have access to it. However, I might also share parts of the raw anonymized data with other researchers if there is a need to do so. The data will be kept securely stored for a minimum period of 10 years on storage systems within the University of Canterbury, and securely destroyed after that.

The outcomes of this research may be published in scientific outlets such as conferences and journals as well as part of my Ph.D. thesis. A thesis is a public document and will be available through the UCLibrary. Major dissemination of this research will be announced on the Facebook page of the HIT Lab NZ (www.facebook.com/HITLabNZ) where a link to the published documents will be provided.

Please indicate to the researcher on the consent form if you would like to receive a copy of the summary of results of the project.

The project is being carried out as a requirement for a Ph.D. degree in Human Interface Technology by Bhuvaneswari Sarupuri under the supervision of Professor Rob Lindeman (gogo@hitlabnz.org) and Dr. Simon Hoermann (simon.hoermann@canterbury.ac.nz). They will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and return it before commencing the experiment.

Department: HIT Lab NZ
Telephone: +64 3 369 0219
Email:
bhuvan.sarupuri@pg.canterbury.ac.nz
07/05/209

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Comfortable and usable locomotion techniques in VR
Consent Form for participant

- ☐ I have been given a full explanation of this project and have had the opportunity to ask questions.
- ☐ I understand what is required of me if I agree to take part in the research.
- ☐ I understand that participation is voluntary and I may withdraw at any time without penalty. Withdrawal of participation will also include the withdrawal of any information I have provided should this remain practically achievable.
- ☐ I understand that any information or opinions I provide will be kept confidential to the researcher Bhuvaneswari Sarupuri, Rob Lindeman, Sungchul Jung, Simon Hoermann and Mary C Whitton and that any published or reported results will not identify the participants.
- ☐ I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form and will be destroyed after 10 years.
- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I understand that I can contact the researcher Bhuvaneswari Sarupuri (bhuvan.sarupuri@pg.canterbury.ac.nz, +64 3 364 2349) or supervisor Professor Rob Lindeman (gogo@hitlabnz.org, +64 3 364 2403) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
- ☐ I would like a summary of the results of the project.
- ☐ By signing below, I agree to participate in this research project.

Name:______________________________Signed:____________________________Date:________________

Email address *(for report of findings, if applicable)*:_

____

Participant number#________

Pre Experiment Questionnaire

1. Age ___
2. Gender (Male/Female/Prefer not to specify)
3. Have you used any Virtual Reality headsets before?
   - ☐ Not at all
   - ☐ Few times a year
   - ☐ Few times a month
   - ☐ Few times a week
   - ☐ Daily
4. What is used any Virtual Reality headsets for gaming before?
   - ☐ Not at all
   - ☐ Few times a year
   - ☐ Few times a month
   - ☐ Few times a week
   - ☐ Daily
5. Have you used a game controller or joystick to navigate in video games?
   - ☐ Not at all
   - ☐ Few times a year
   - ☐ Few times a month
   - ☐ Few times a week
   - ☐ Daily
6. Have you ever used a game controller or joystick to navigate in the virtual world using a Virtual Reality headset?
   - ☐ Not at all
   - ☐ Few times a year
   - ☐ Few times a month
   - ☐ Few times a week
   - ☐ Daily
7. Have you ever used Teleportation to navigate in the virtual world using a Virtual Reality headset?
   - ☐ Not at all
   - ☐ Few times a year
   - ☐ Few times a month
   - ☐ Few times a week
   - ☐ Daily

This form should be completed after reading the *Human Ethics Policy* issued by the Human Ethics Committee available at http://www.canterbury.ac.nz/humanethics

Participant number#________

Condition-

Questionnaire

1. **Rate the following based on how much you agree with the given statement**

Strongly agree — Strongly disagree

Statements	5	4	3	2	1
I think I would like to use this system frequently					
I found the system unnecessarily complex					
I thought the system was easy to use					
I think I would need the support of a technical person to be able to use this system					
I found that various functions in this system were well integrated					
I thought there was too much inconsistency in this system					
I would imagine that most people will learn to use this system very quickly					
I found the system very cumbersome to use					
I felt very confident using the system					
I needed to learn lot of things before I could get going with the system					

HITLabNZ
Human Interface Technology Lab New Zealand
www.hitlabnz.org

SIMULATOR SICKNESS QUESTIONNAIRE

Participant number#________

Instructions : Circle how much each symptom below is affecting you right now.

1.	General discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Headache	None	Slight	Moderate	Severe
4.	Eye strain	None	Slight	Moderate	Severe
5.	Difficulty focusing	None	Slight	Moderate	Severe
6.	Salivation increasing	None	Slight	Moderate	Severe
7.	Sweating	None	Slight	Moderate	Severe
8.	Nausea	None	Slight	Moderate	Severe
9.	Difficulty concentrating	None	Slight	Moderate	Severe
10.	Fullness of the Head	None	Slight	Moderate	Severe
11.	Blurred vision	None	Slight	Moderate	Severe
12.	Dizziness with eyes open	None	Slight	Moderate	Severe
13.	Dizziness with eyes closed	None	Slight	Moderate	Severe
14.	*Vertigo	None	Slight	Moderate	Severe
15.	**Stomach awareness	None	Slight	Moderate	Severe
16.	Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

NASA-TLX Mental Workload Rating Scale

Please place an "X" along each scale at the point that best indicates your experience with the display configuration.

Mental Demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc)? Was the mission easy or demanding, simple or complex, exacting or forgiving?

Low High

Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the mission easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low High

Temporal Demand: How much time pressure did you feel due to the rate or pace at which the mission occurred? Was the pace slow and leisurely or rapid and frantic?

Low High

Performance: How successful do you think you were in accomplishing the goals of the mission? How satisfied were you with your performance in accomplishing these goals?

Low High

Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low High

Frustration: How discouraged, stressed, irritated, and annoyed versus gratified, relaxed, content, and complacent did you feel during your mission?

Low High